Design and Performance of the at TESLA Test Facility Collimation System

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1. Motivations for the collimation system
2. Layout and Performance
3. Beam Loss System
4. Conclusion

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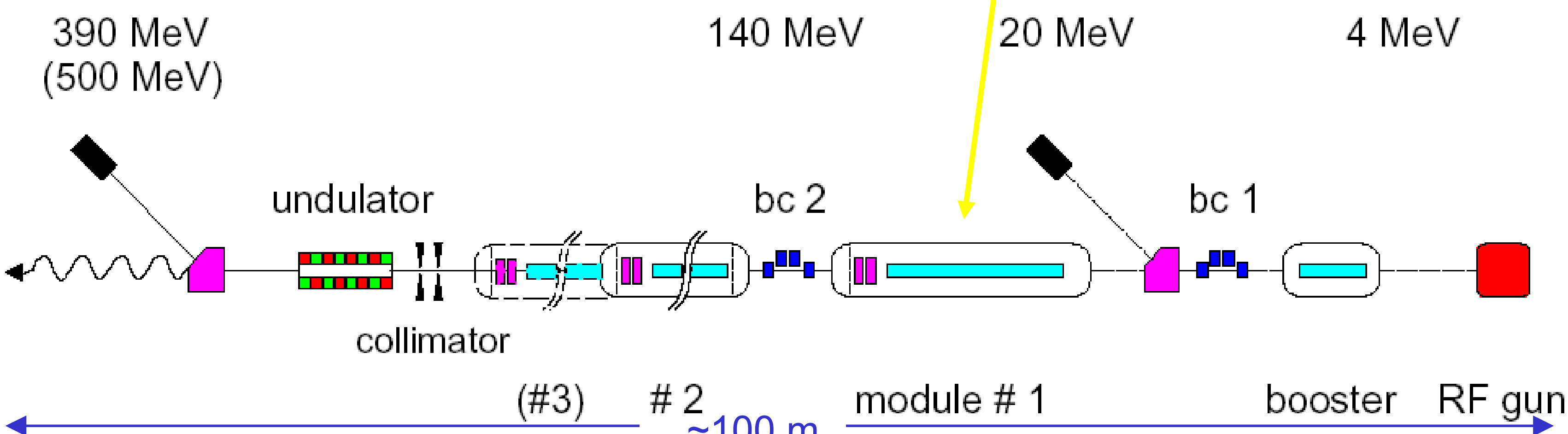
Scheme of TTF Linac Phase I

Goals: - Test Facility for SC-modules
- Proof-of-principle for SASE-FEL in VUV

- RF photo-injector (laser, gun, booster, bc1)
- Two superconducting acceleration modules
- Magnetic chicane (BC2)
- Two stage spoiler absorber collimation system
- Three undulator modules
- Photon diagnostics

Installation: 04/99

Operated: 06/99 - 05/02



Motivations for the collimation system

Major concern:
Radiation damage of NdFeB permanent magnets

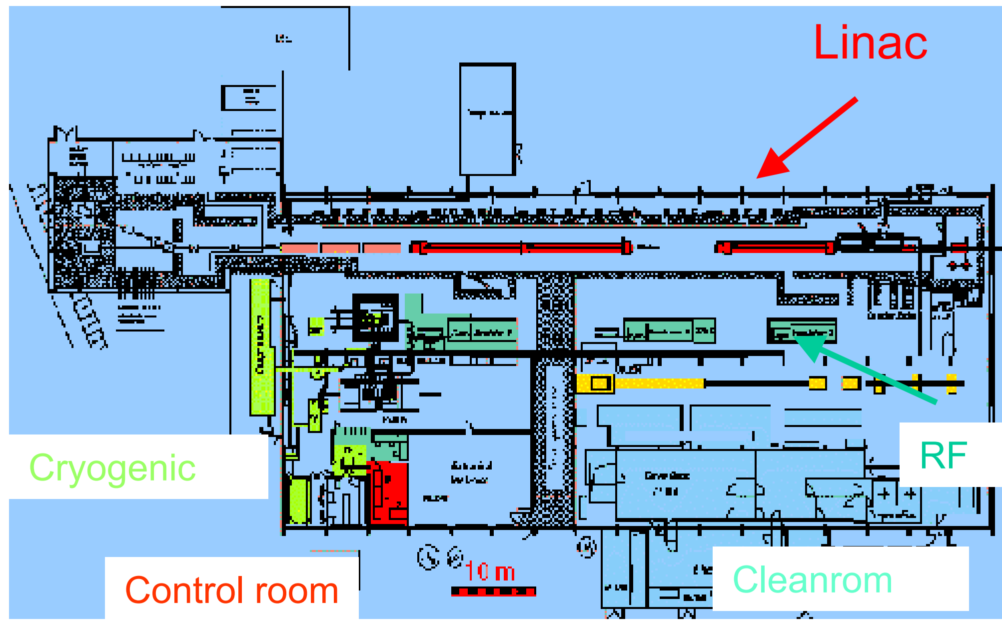
Design beam parameter:

	TTF	FEL	Used
Bunch spacing	1 μs	0.11μs	0.44/1 μs
Beam current	8 mA	9 mA	3-7 mA
Bunch charge	8 nC	1 nC	2-4 nC
norm. emittance	20 μm	2 μm	3-10 μm
Beam Energy	150 - 500 MeV		250 MeV
Beam duration	800 μs		10-800 μs
Repetition rate	10 Hz		1 Hz
Beam power	10 - 36 kW		<1.4 kW

Critical issues to be considered:

- absorbed dose in magnets < 70 kGy
- vacuum leak due to material crack < 2 - 6 μs
- radiological dose outside tunnel < 20-100 W
- to be design, manufactured and installed < 2a

⇒ additional active and passive protection required



Motivation for the collimation system
- Radiation hardness of NdFeB magnets -

Various experiments:

Co - source: γ 1.1 MeV and 1.3 MeV

< 10 MGy no effect

Osaka: (Okuda et.al) 17 MeV electrons

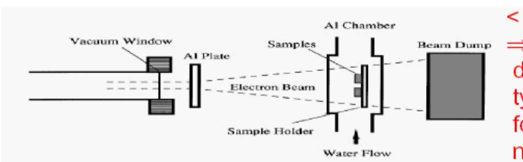
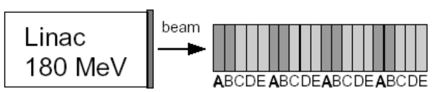


Fig. 1. Experimental setup for the electron-beam irradiation.

< 2.8 MGy
$\Rightarrow$ demagnetization depends on magnet type
for type used in TTF no effect

TTF dispersive section: 10-30 MeV electrons < 800 kGy no demag.

ESRF: 180 MeV electrons

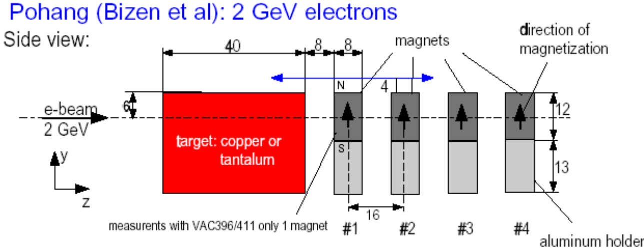


A: Vacomax 145
B: Vacomax 225
C: Vadodym 351
D: Vacodym 370
E: Vacodym 400

type E: 65 kGy (>20 MeV) $\Rightarrow$ 1 % remanent loss

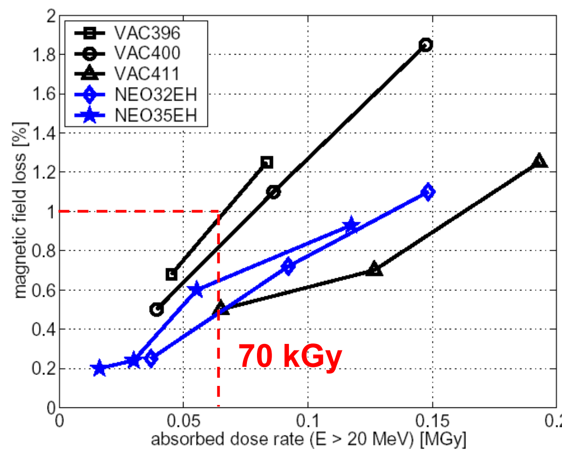
Pohang (Bizen et al): 2 GeV electrons

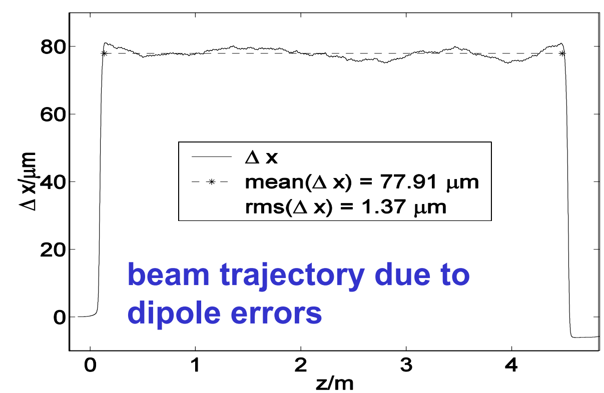
Side view:



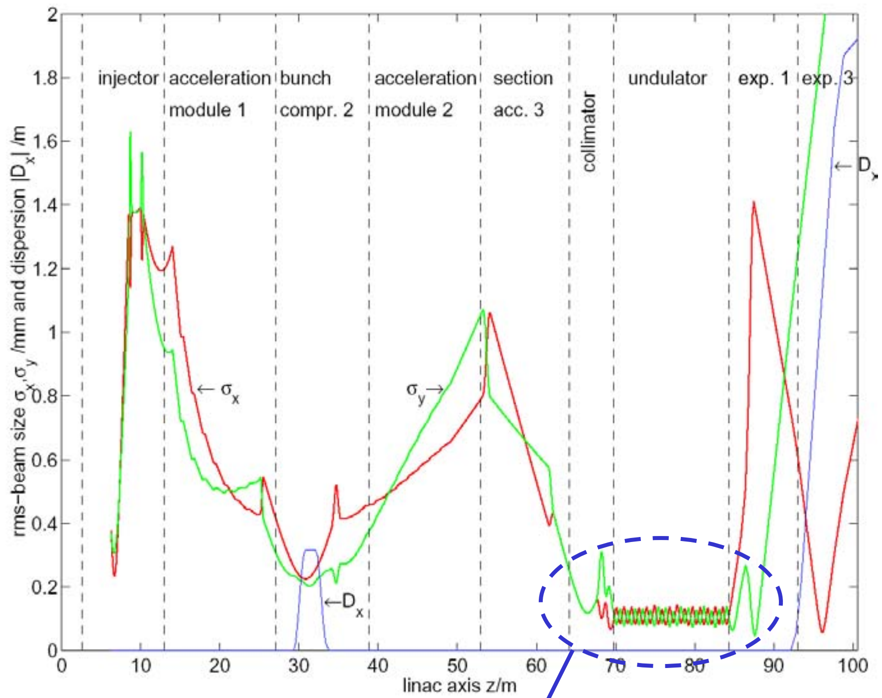
TTF type 70 kGy (>20 MeV) $\Rightarrow$ 1 % remanent loss
but discrepance if tantalum is used

- Demagnetization strongly dependent on NdFeB type and the radiation fields
- Requires the definition of an equivalent absorbed dose
- e^-, γ < 20 MeV no effects
- 2 GeV $\rightarrow$ hadron release can become critical
- overlap between electron and photon beam better than 20μm $\rightarrow$ 0.1-0.5% field changes





Motivation for the collimation system
- Instantaneous heating -

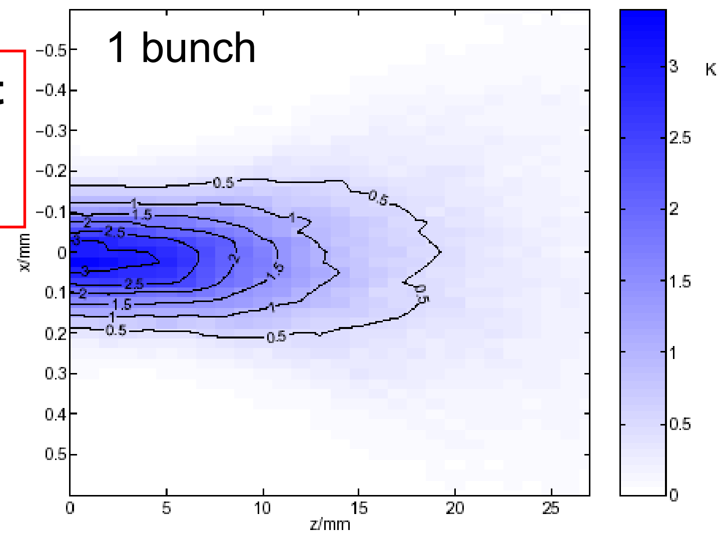


<u>FEL design parameter:</u>

Bunch spacing	111 ns
Train duration	800 μs
Charge	1.0 nC
Norm. emittance	2.0 μm

Spoiler could withstand 6 μs beam at design optics (β=2.5m): Aluminum, 90 μm rms, 300 MeV

Cracks from front to back unlike to linear colliders

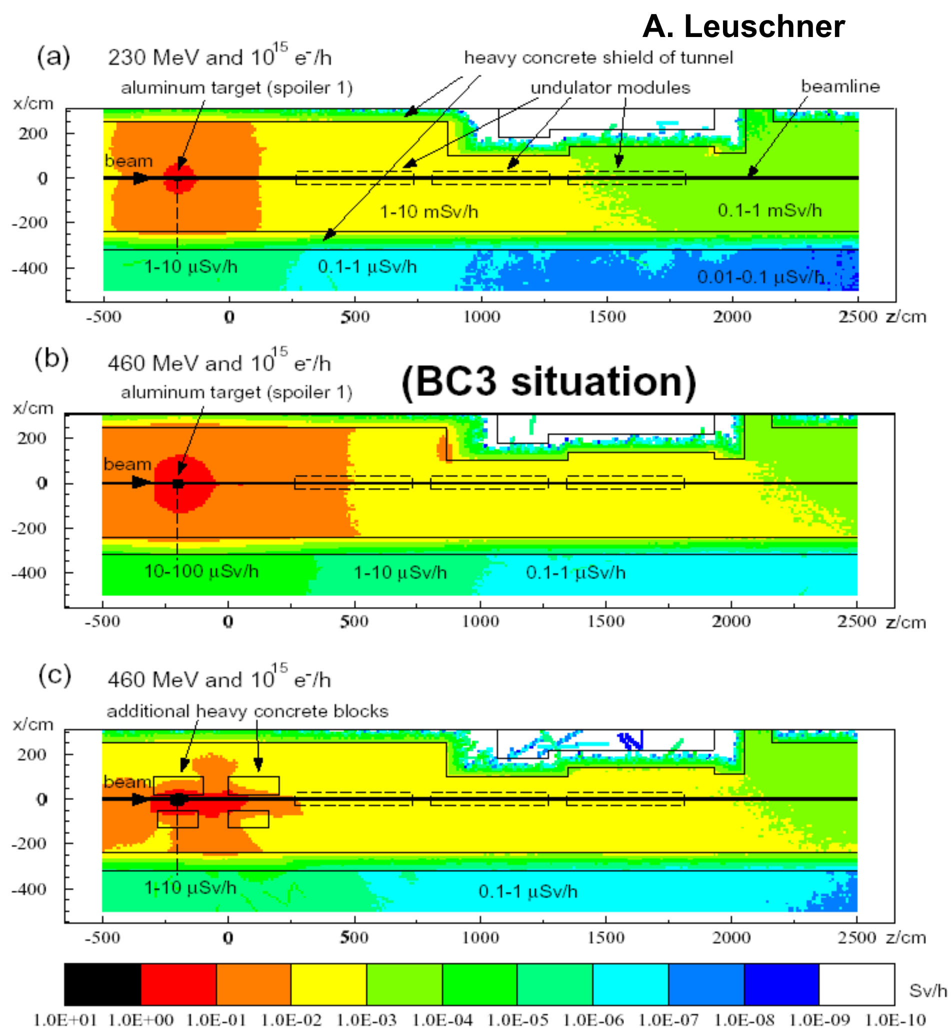


Worse case scenario: Beam sizes of 60 μm rms could crack aluminum within 2.5 μs, copper 1.25 μs chamber of undulator 2.0 μs, etc.

Motivations for the collimation system - radiation outside tunnel shields -

- ***High energy neutrons dominates equivalent dose level outside tunnel shielding***
- ***230 $\rightarrow$ 460MeV onset of photopion production mechanism (resonance at 300MeV)***
- ***Heavy concrete shields to be added to tunnel shields***
- ***< 10 μSv/h required***

$\Rightarrow$ additional heavy concrete shields surrounding the collimator required



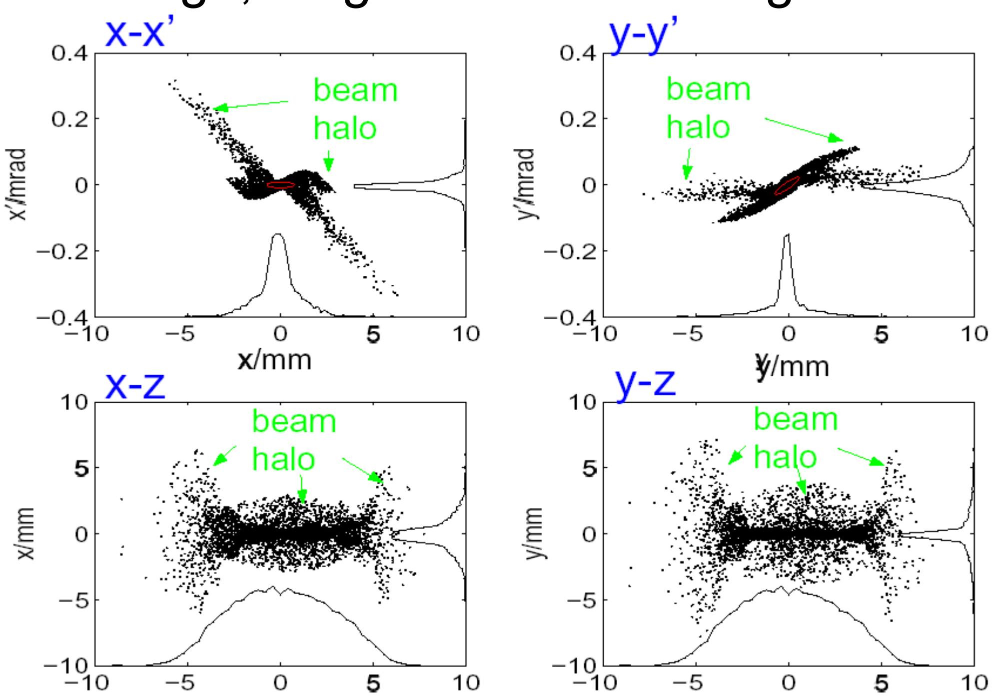
Hadron radiation dose for 10^{15} e^-/h (0.06% I_{nom})

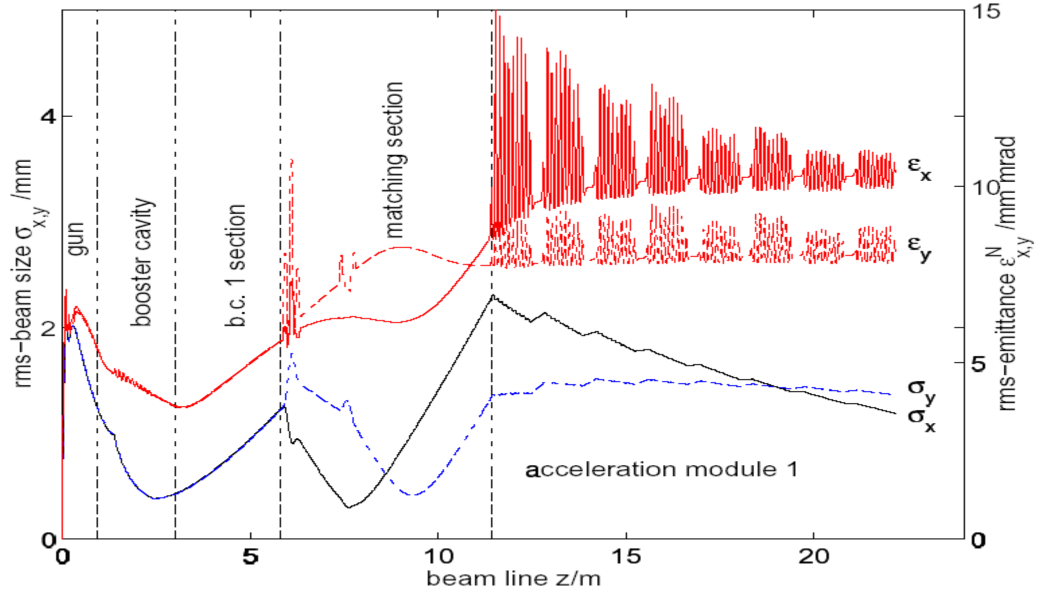
energy	tunnel shield only	+ concrete blocks
230 MeV	10 µSv/h	1 µSv/h
460 MeV	100 µSv/h	10 µSv/h

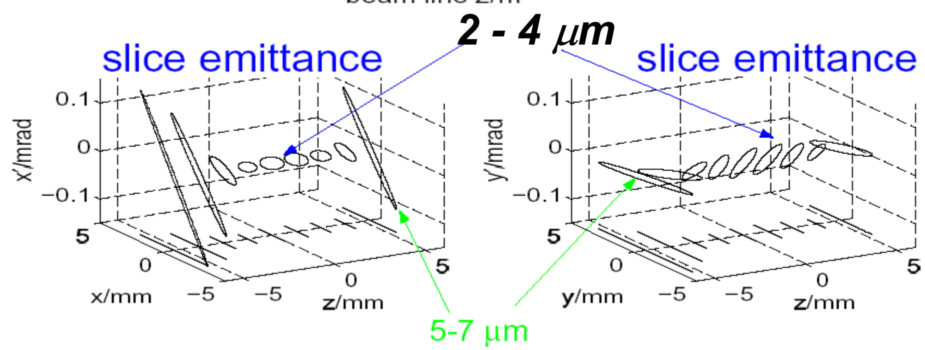
=> at 230 MeV $I_{loss} \leq 0.6\ \% \cdot I_{nom}$

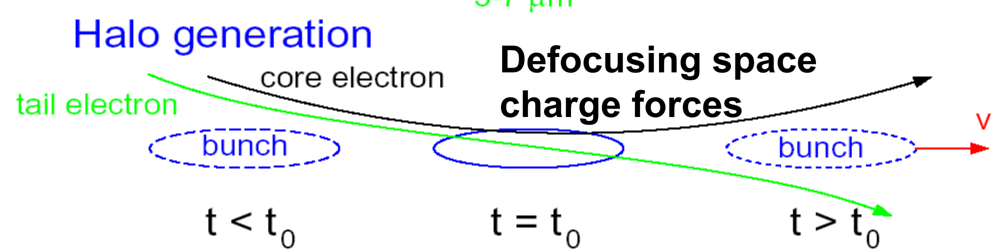
Generation of beam halo in a RF-gun

- Example: FEL run 04/2000
- Bunch charge 1 nC
- Small slice emittance but large projected emittance due to beam halo
- Halo formation very sensitive to charge, magnets and rf settings.



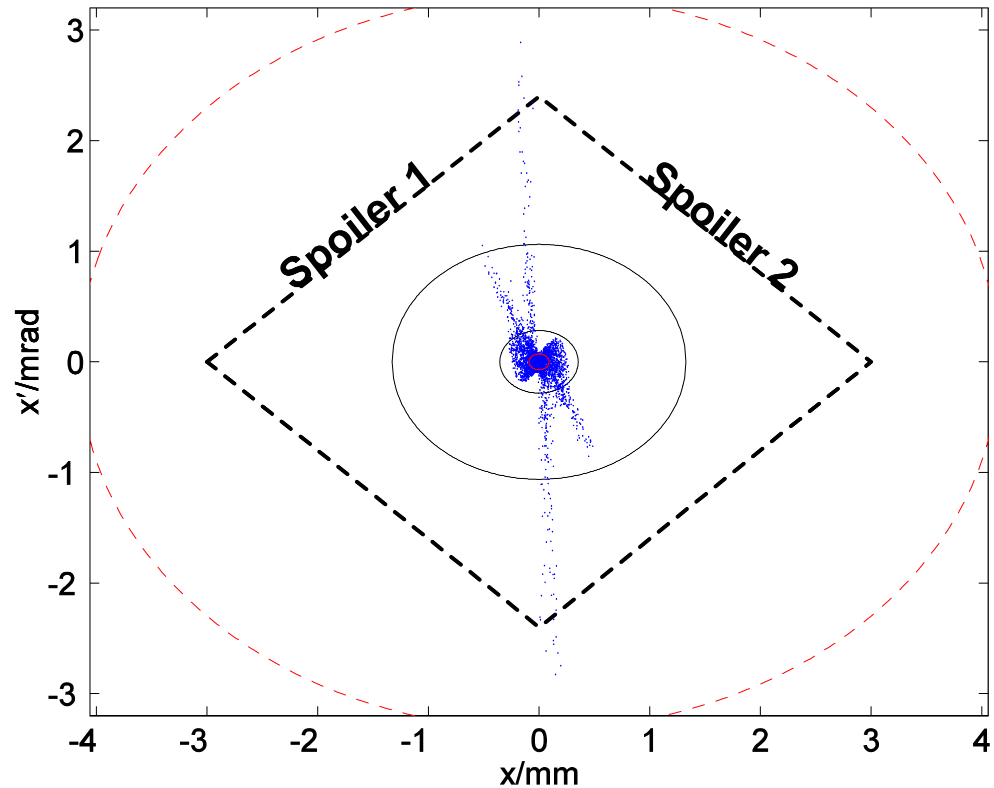






Simulation of the beam halo

- Beam tracked from the rf-gun to the center of the collimator (FEL condition 04/00)
- In example shown 50% of the beam (core) is perfectly matched to the undulator
- In this case about 0.5% of beam cannot pass the collimators (about 80 W for nominal beam current)



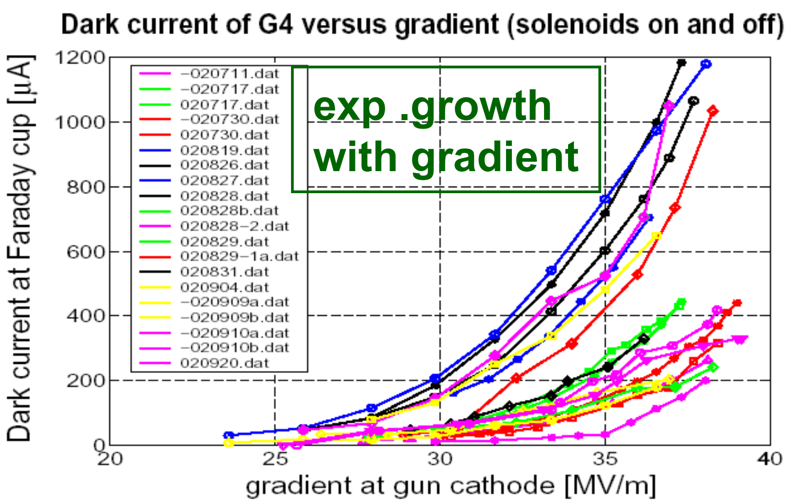
- Operational experience during FEL runs with saturation:

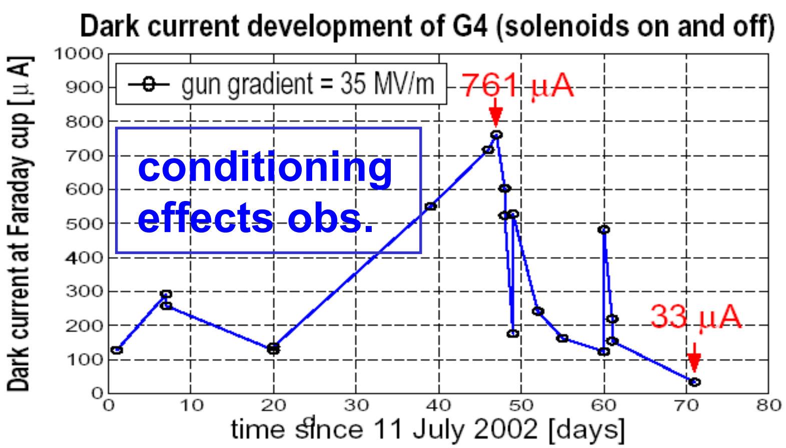
  losses of a few percent at the collimator section

- no CSR effects included in simulation

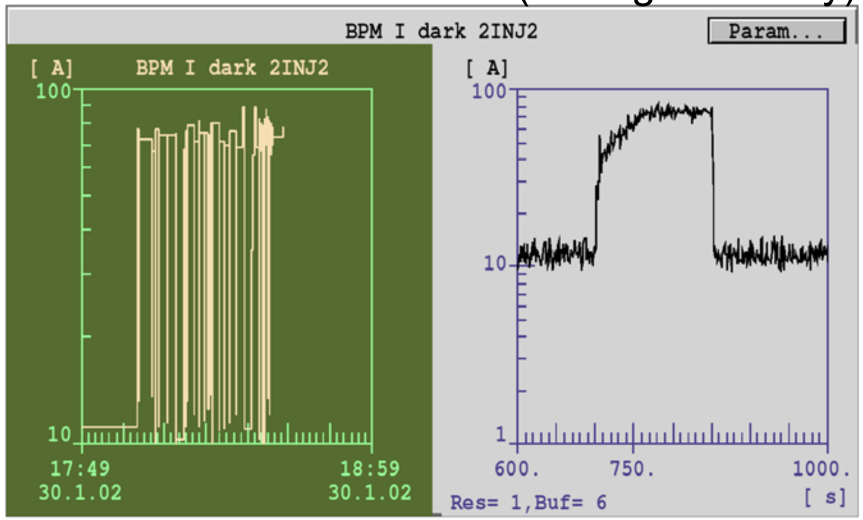
Dark Current from RF-gun

- emitted dominantly from gun back plane
- can be in same order as beam current
- few percent is accelerated to the dump

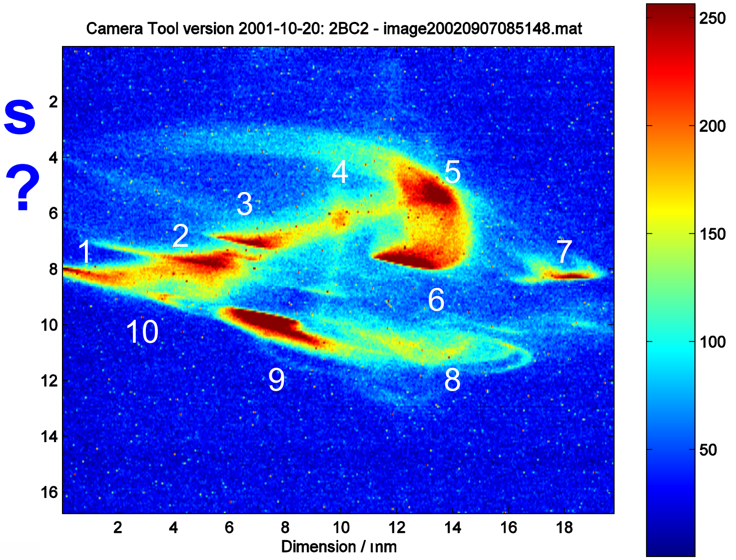




Dark current monitor (C.Magne Saclay)



Which one is the beam???



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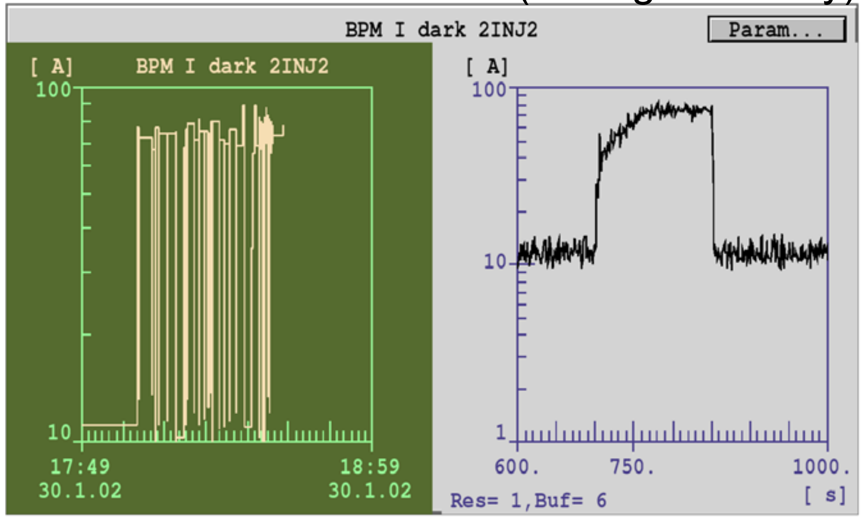
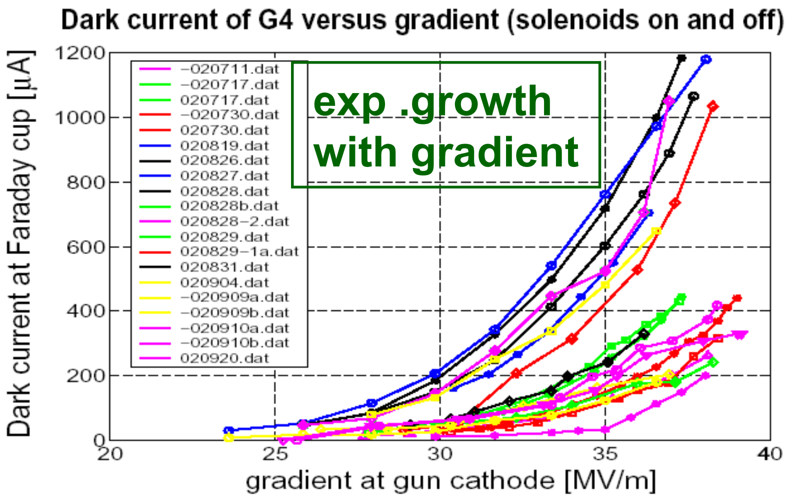
Dark Current from RF-gun

- emitted dominantly from gun back plane
- can be in same order as beam current
- few percent is accelerated to the dump

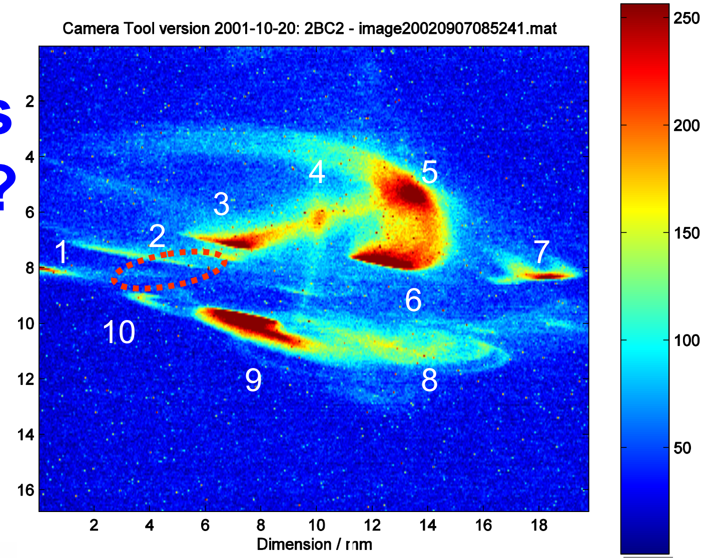
Dark current monitor (C.Magne Saclay)

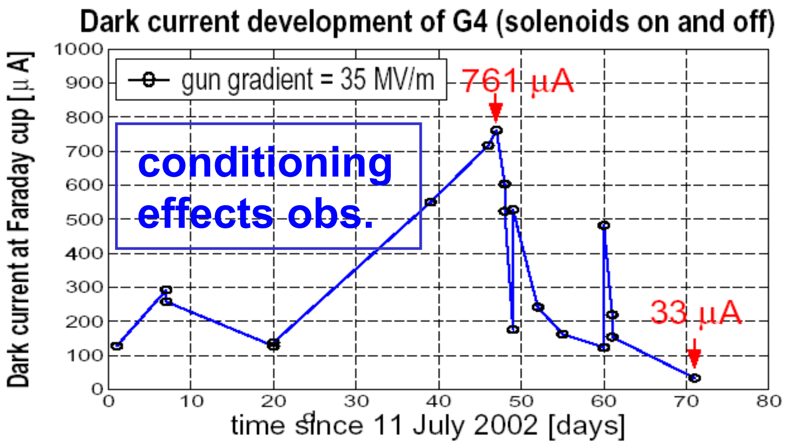




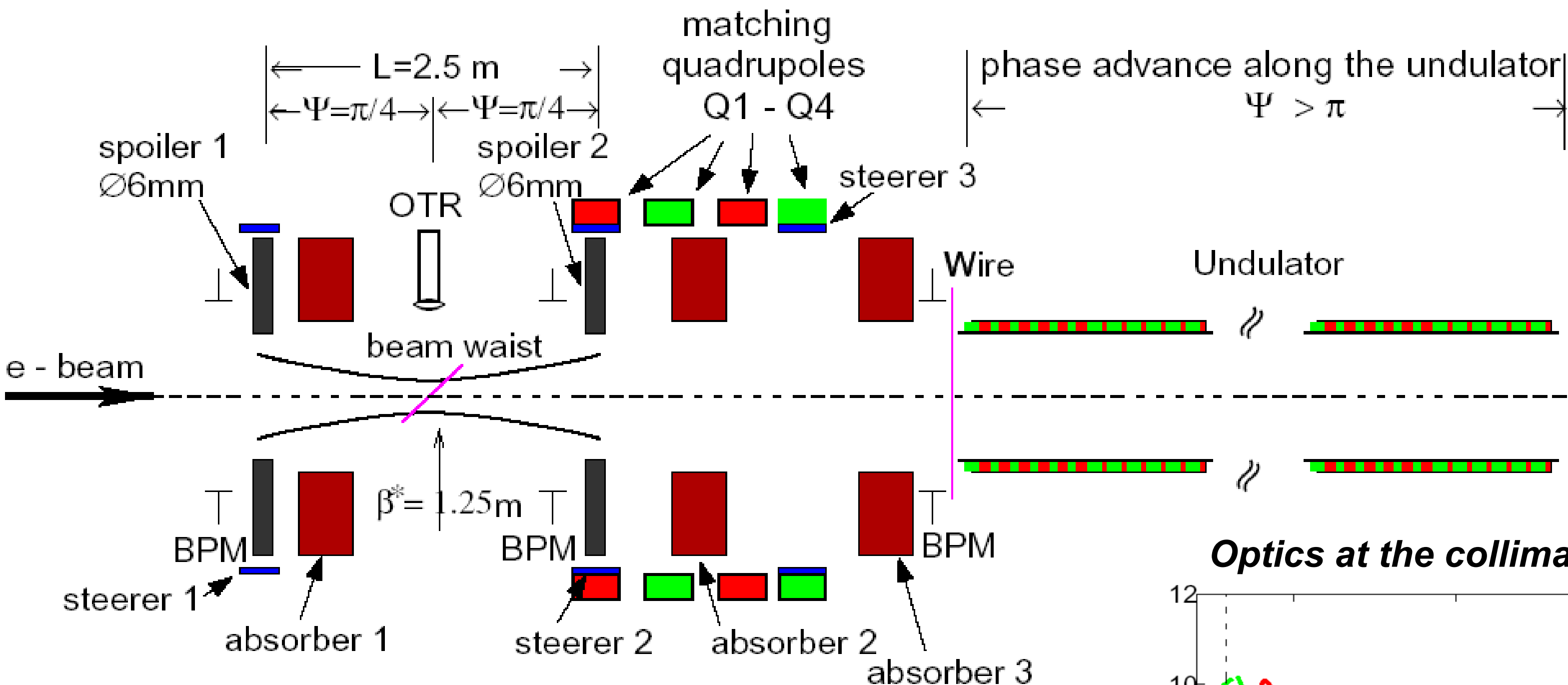
Which one is the beam???

Number 2

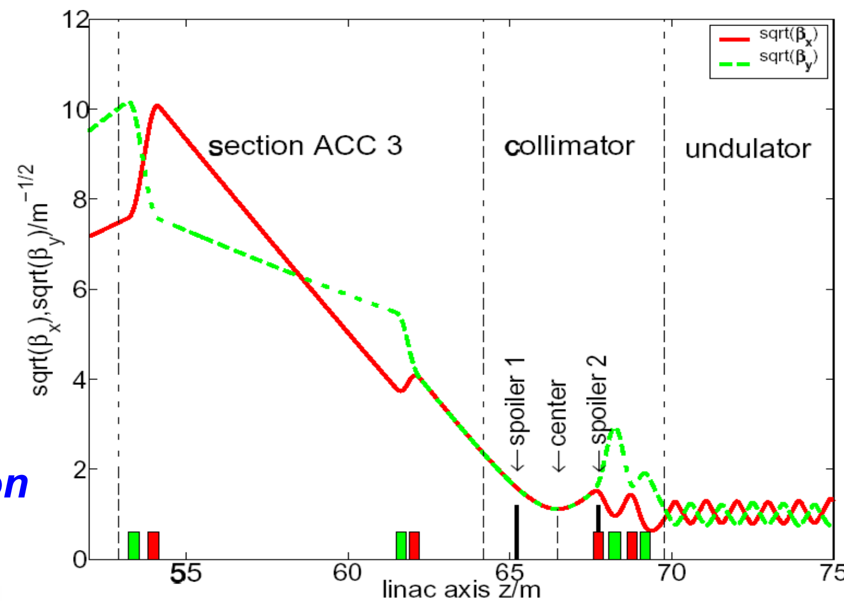




Scheme of the collimation section

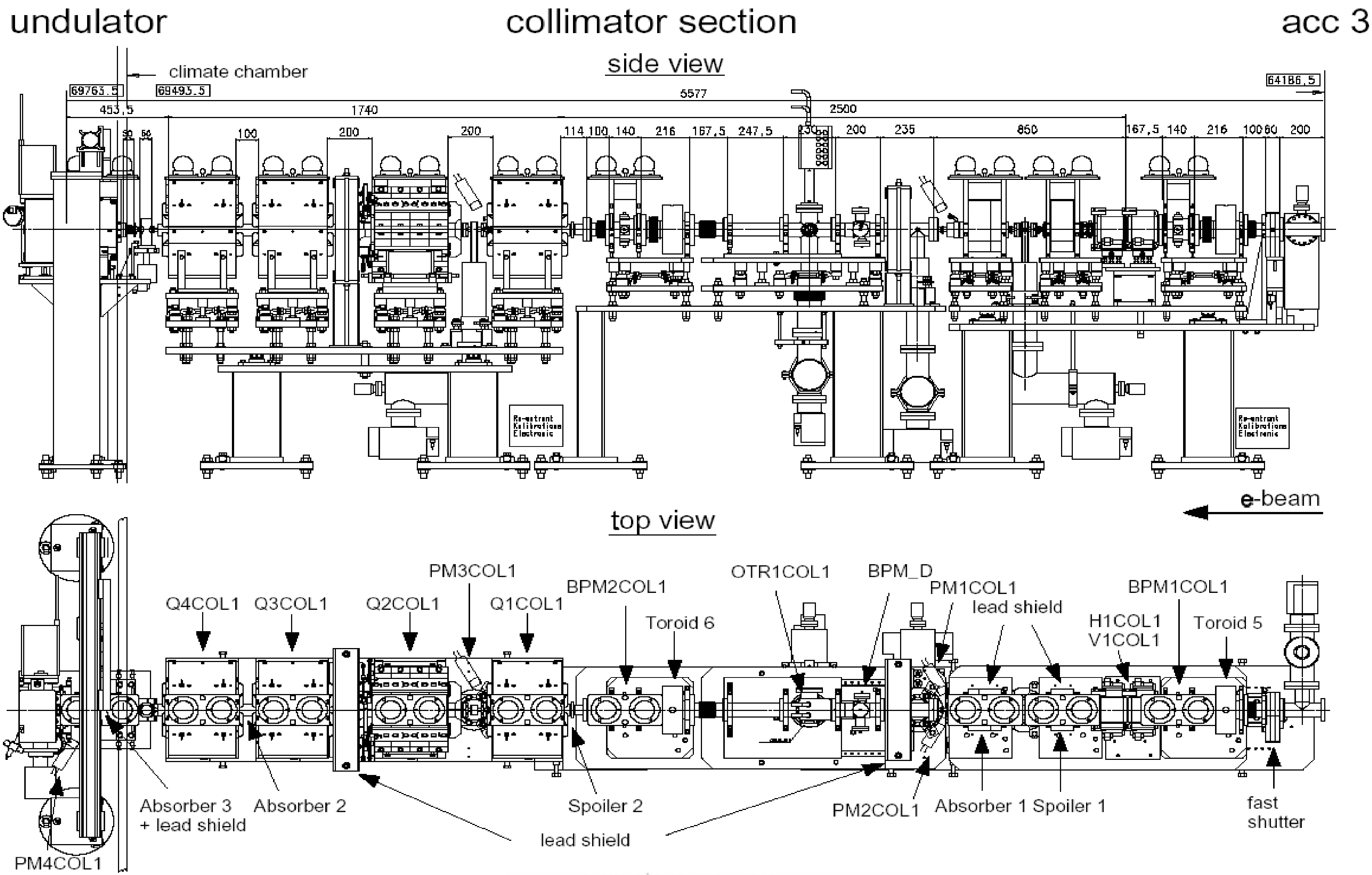


Optics at the collimator section:

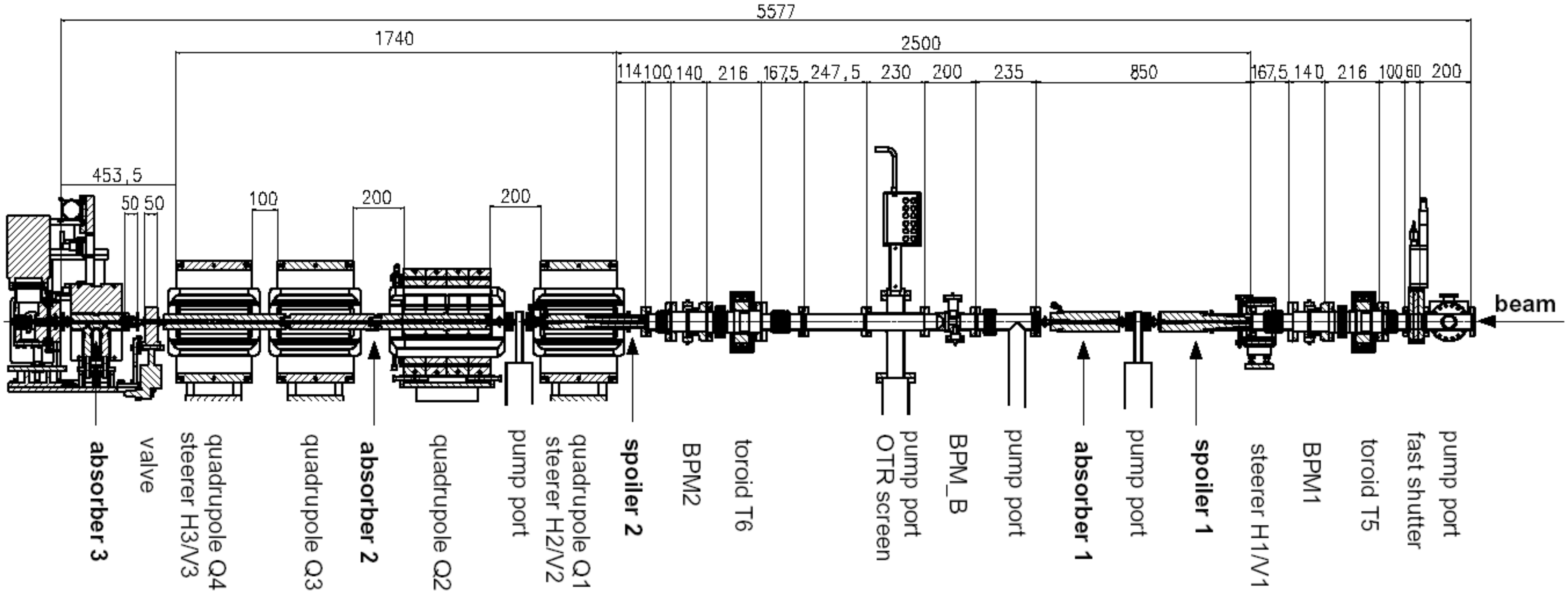


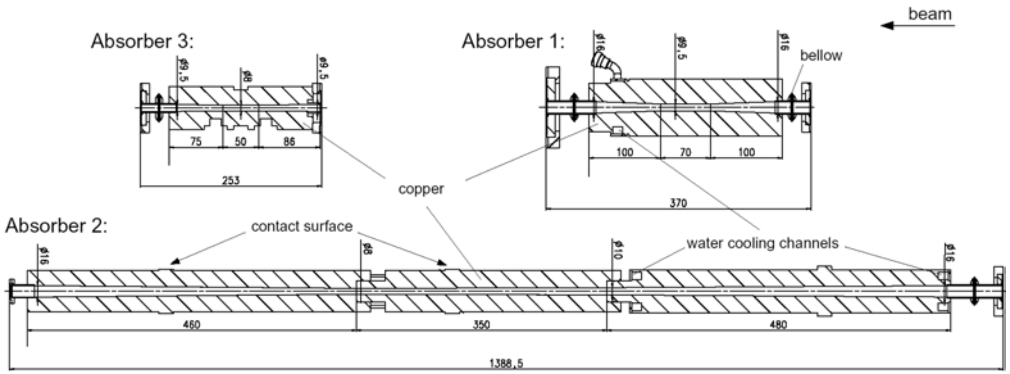
- ***2 spoilers to restrict the phase space acceptance***
- ***2 absorber to remove secondary particles***
- ***4 quadrupoles for optics match to undulator***
- ***2 bpms to center beam in the spoilers***
- ***1 OTR-screen to match beam into collimator***
- ***4 steerers to correct for quadrupole misalignments***
- ***toroids and photomultiplier to monitor the transmission***
- ***water cool and temperature controlled***

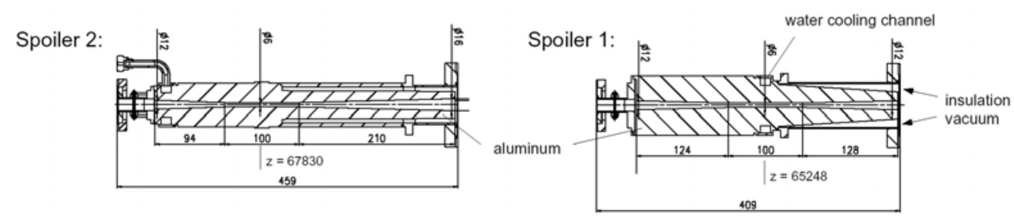
Drawing of the collimator section



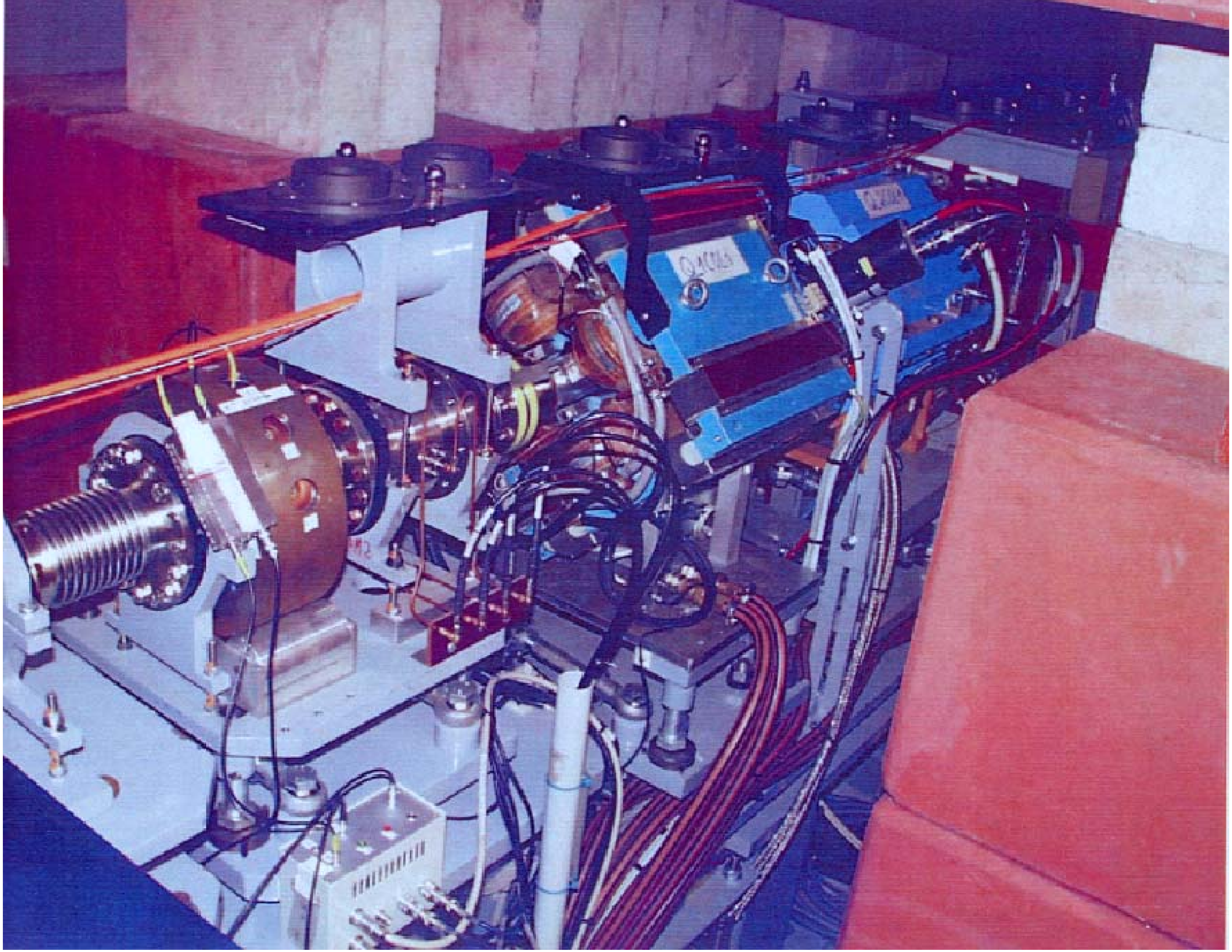
Drawing of the collimator section





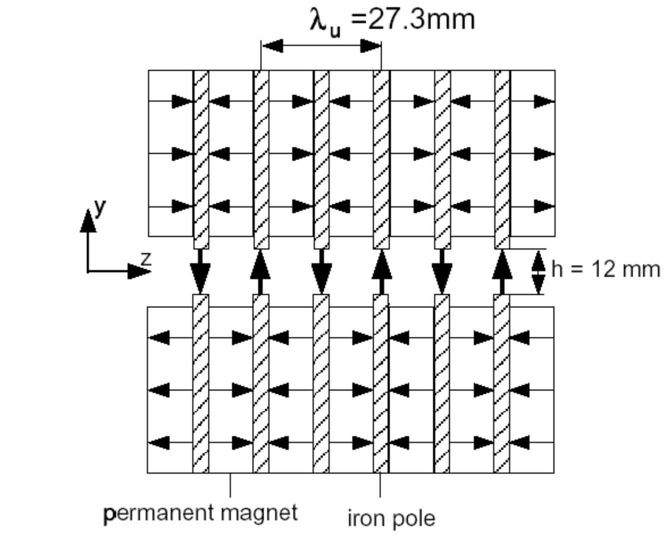


collimator diameters				
spoiler 1	spoiler 2	absorber 1	absorber 2	absorber 3
6 mm	6 mm	9.5 mm	8 mm	8 mm

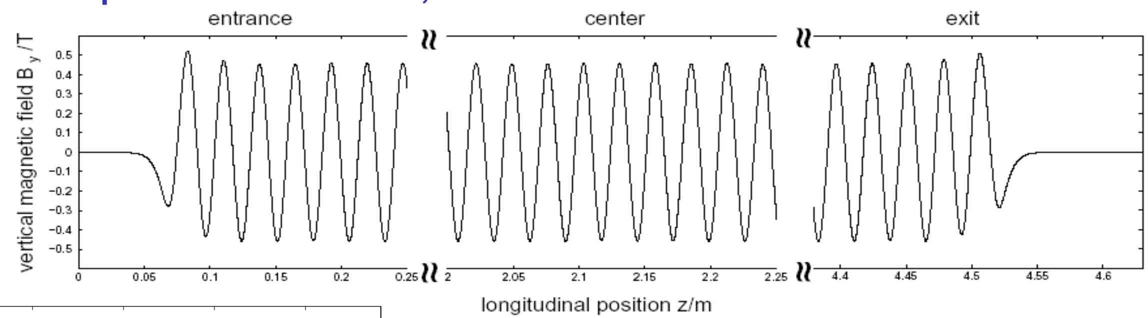


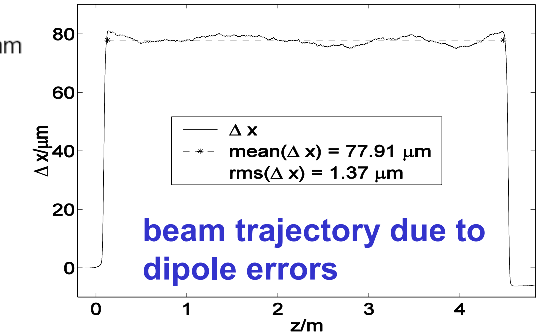
Magnetic Properties of the Undulator

hybrid magnet:



Dipole field at entrance, center and exit of undulator

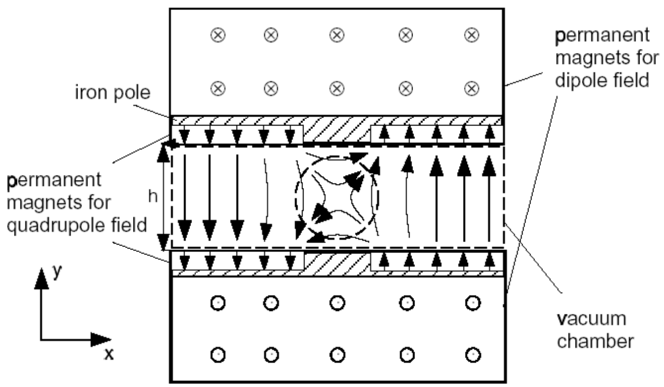




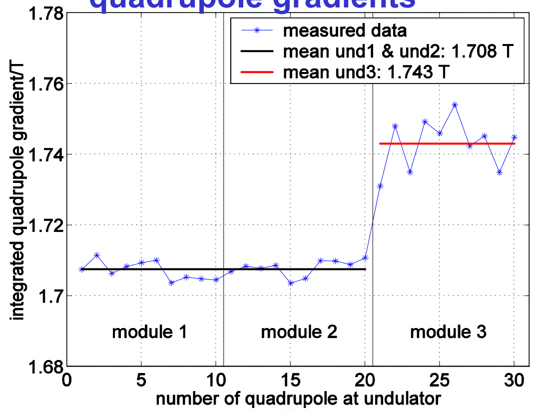
content of high harmonics

first harmonic	$B_0 b_1$	454.0 mT	b_1	0.9908
third harmonic	$B_0 b_3$	4.455 mT	b_3	0.0097
fifth harmonic	$B_0 b_5$	-0.248 mT	b_5	-0.0005

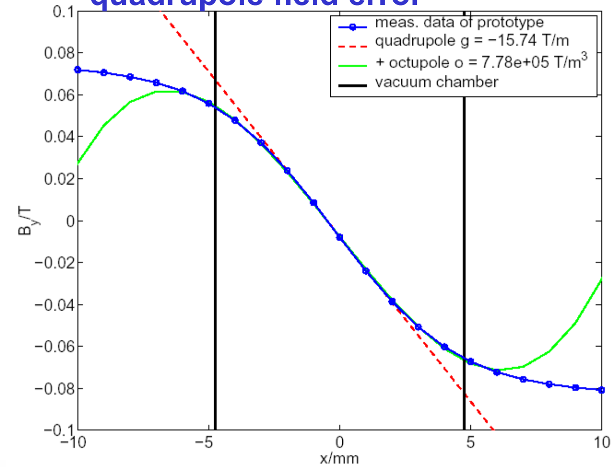
quadrupole magnets:



quadrupole gradients

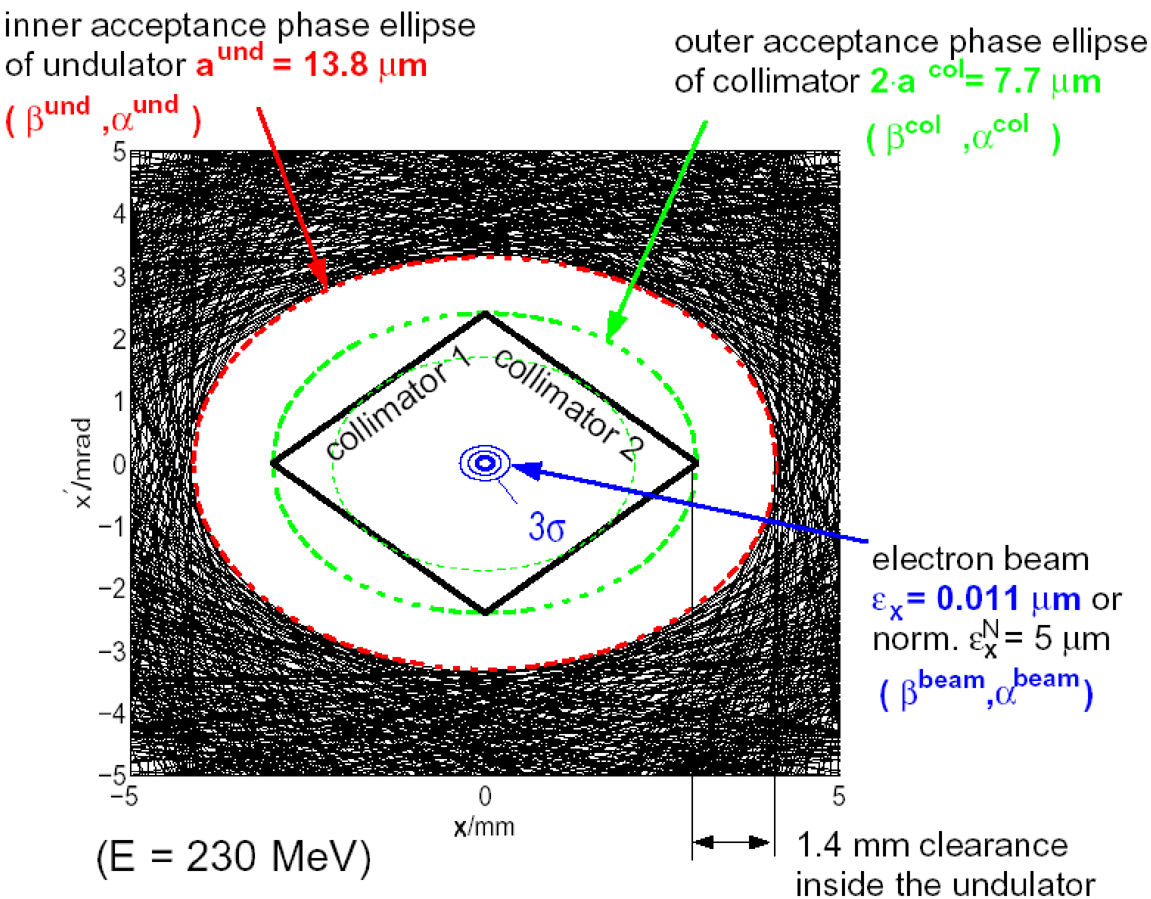


quadrupole field error

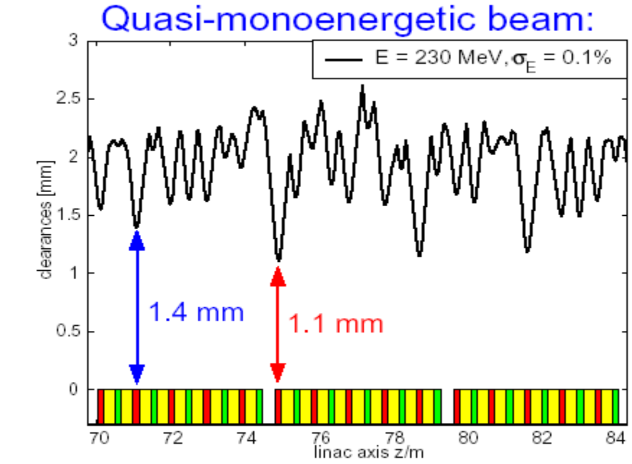


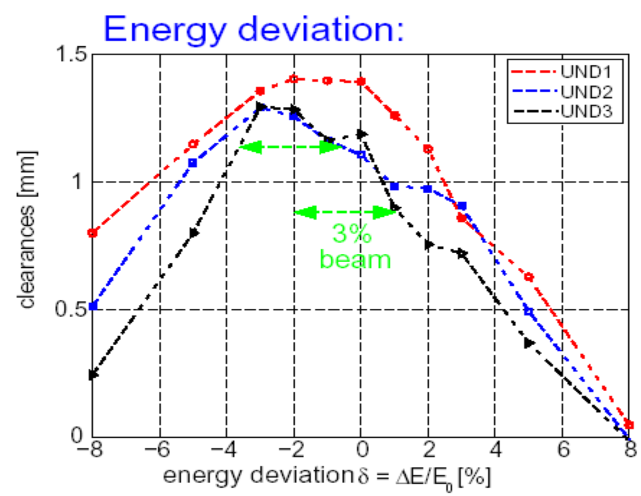
Performance of the collimator

- Phase space acceptance



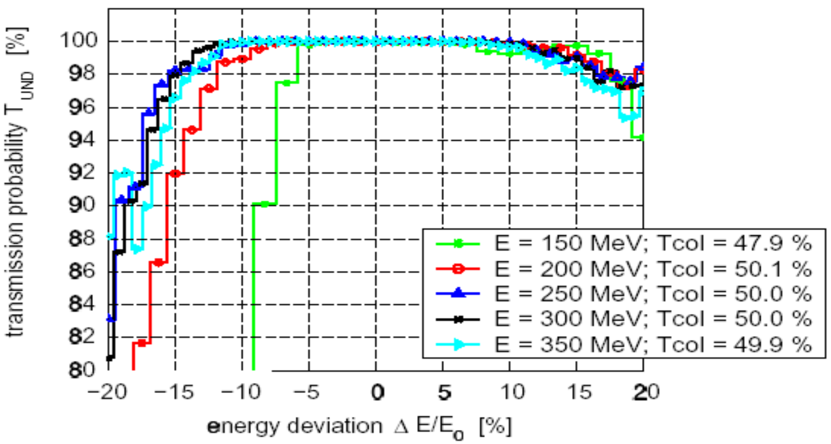
- Clearance of collimated beam to undulator vacuum chamber:



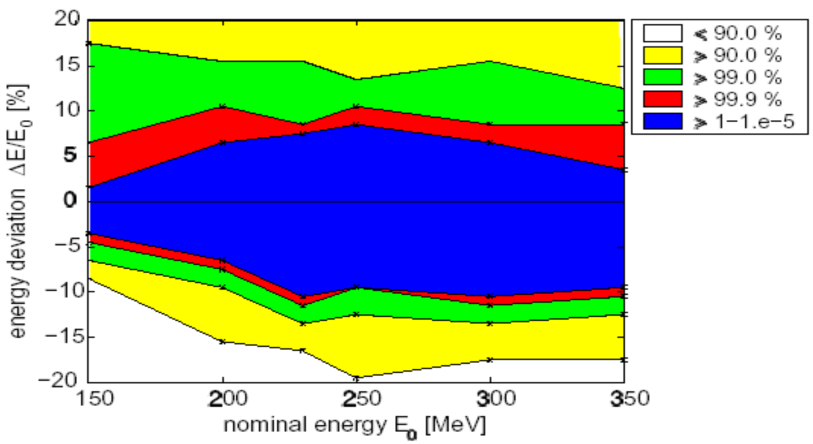


Performance of the collimator

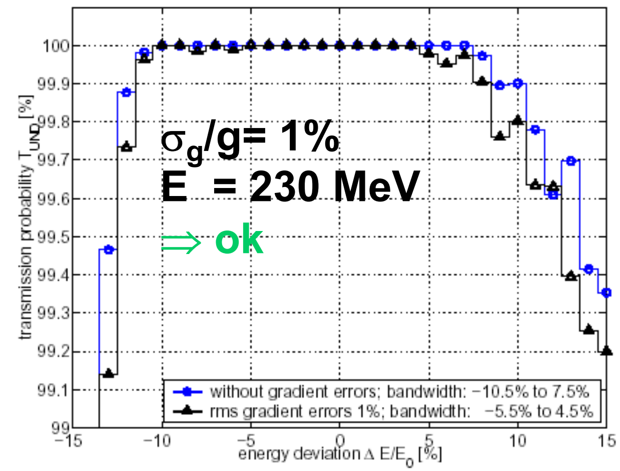
- ## Energy acceptance
  - halo emittance $\varepsilon = 1.41\,\mu m$
  - beam energy between 150 - 350 MeV



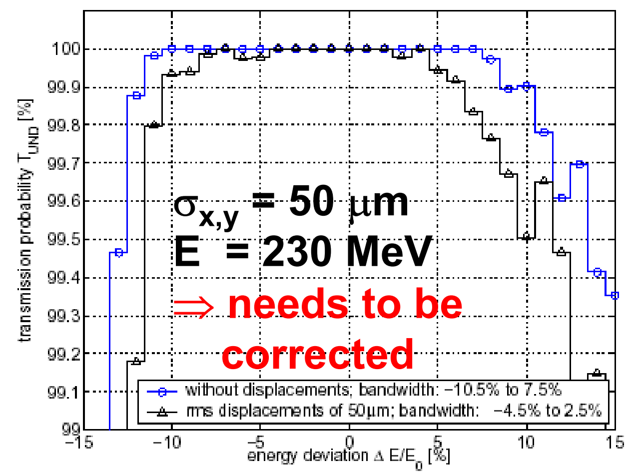
=> losses are asymetrical w.r.t. $\Delta E/E$



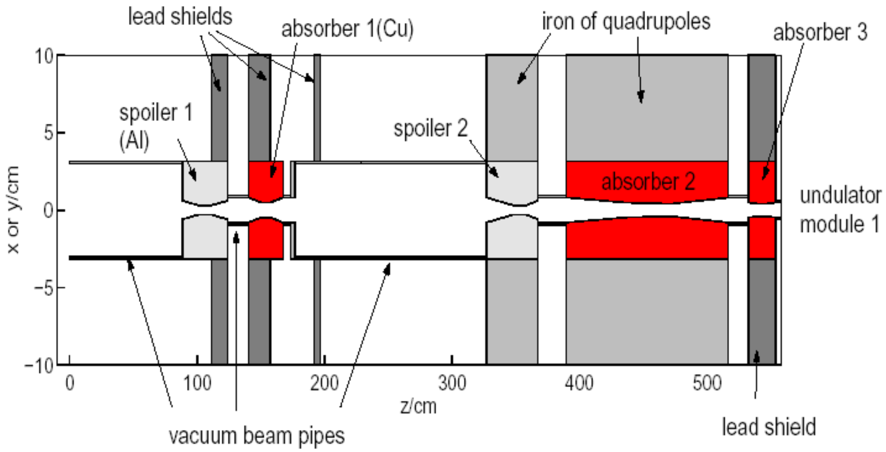
- ## Gradient errors of quads



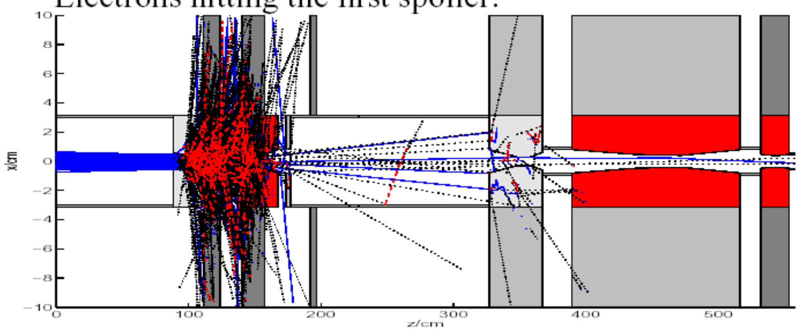
- ## Displacements of quads



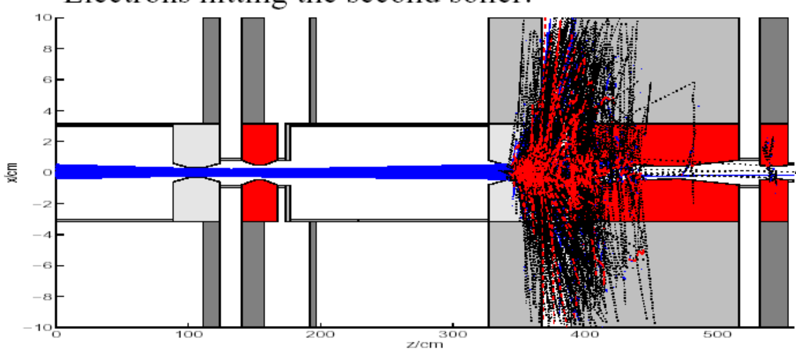
Secondary particle efficiency

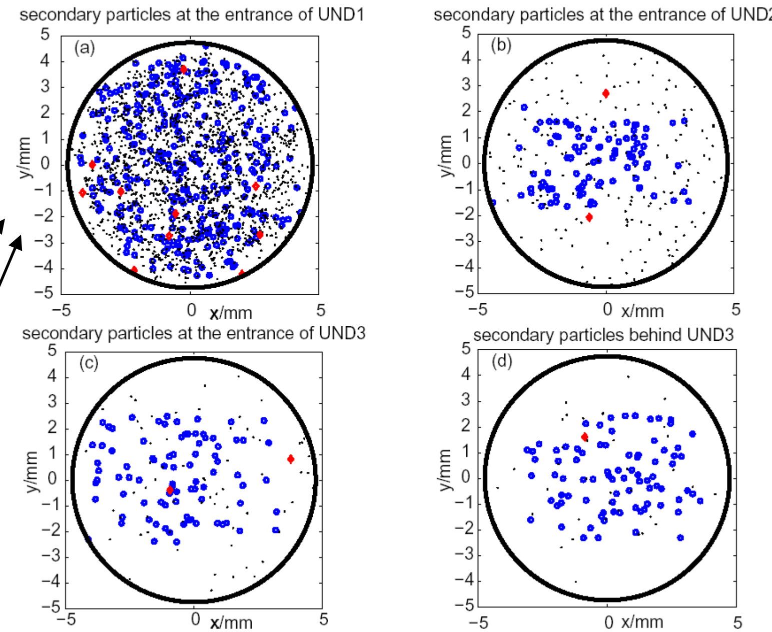


Electrons hitting the first spoiler:



Electrons hitting the second soiler:





E= 230 MeV, T_{col}= 50%

energy deposition and transmission of secondary particles [%]			
	e^- incidence on spoiler 1 $E_{dep,1}$ [%]	e^- incidence on spoiler 2 $E_{dep,2}$ [%]	1 kJ energy incident on the spoilers $57.6\% \cdot E_{dep,1} + 42.2\% \cdot E_{dep,2}$ [J]
spoiler 1	52.5	0.0	302.1
spoiler 2	1.8	43.9	196.3
absorber 1	17.3	0.0	100.0
absorber 2	0.2	22.8	97.6
absorber 3	0.0	0.5	2.2
beam pipes	3.0	4.2	35.0
lead shield	20.5	0.0	118.6
quadrupoles	0.6	16.0	74.4
outside boundary	4.0	12.1	71.8
transmit to undulator	0.04	0.43	2.0
sum	100	100	1000

efficiency ×10 higher for spoiler1

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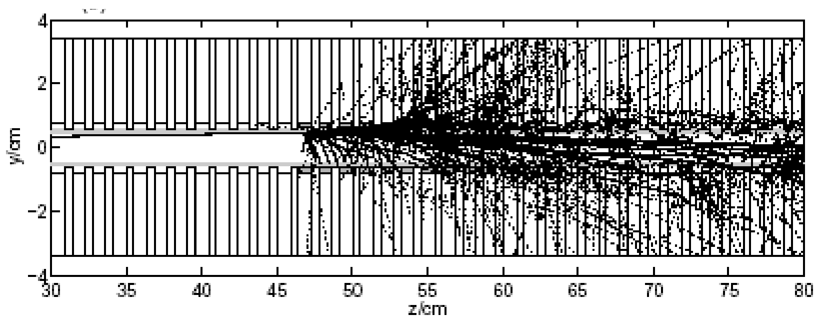
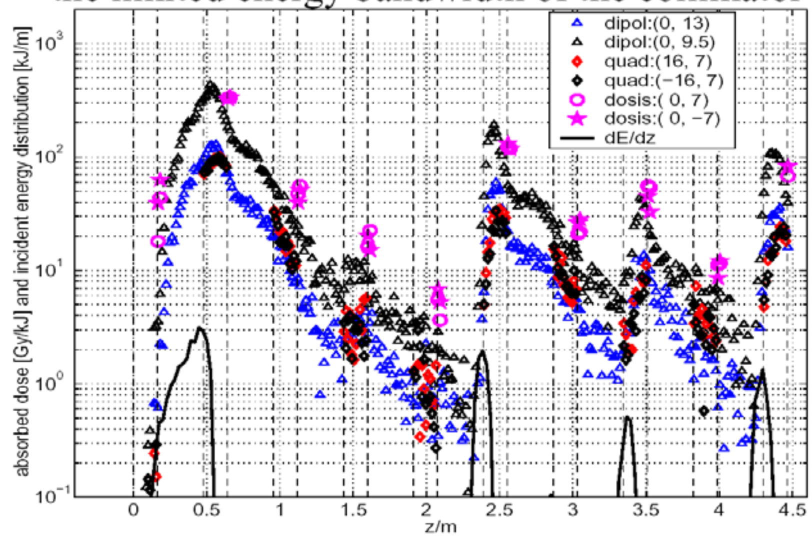
Collimator Performance
- energy deposition in undulator -

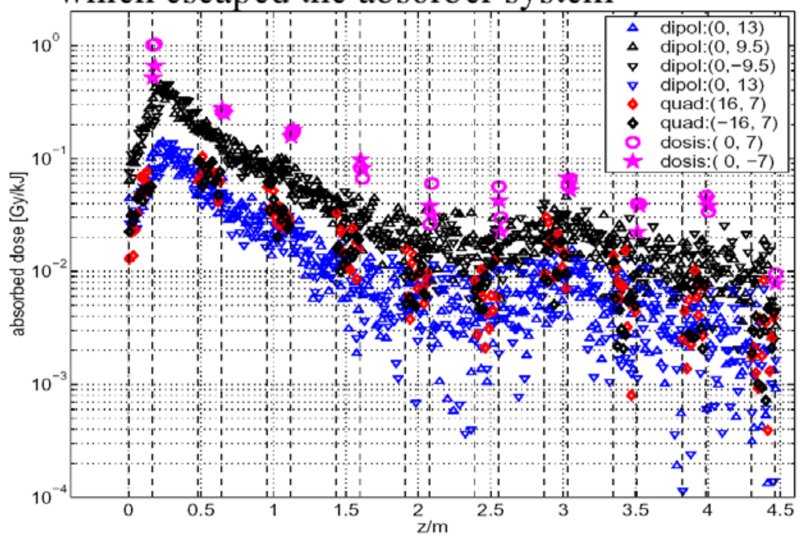
EM-shower in undulator



the limited energy bandwidth of the collimator



secondary particles generated at the spoilers which escaped the absorber system



- ***Gain of about 3 orders in magnitude (primary versus secondary losses)***
- ***Rapid drop of dose in lateral direction***
- ***Pattern strongly dependent on beam loss mechanism***
- ***Simulated dosimeter overestimate deposited dose***
- ***Can be used to identify operation errors of collimator section***

Collimator Performance
- examples for measured dose rates -

Integrated beam current

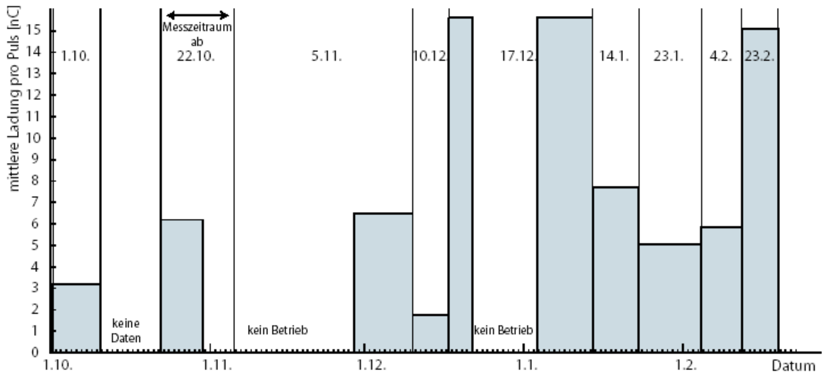


Figure 1: Averaged charge per macro pulse.

- The smallest ration dose versus charge amounts to $5kGy/C$.
- In 4 week with 80% availabilty about 57.6 C is transported
  $\Rightarrow$ 290 kGy is the expected absorbed dose in the undulator after the high gradient long macropulse test.

Dosimeter values

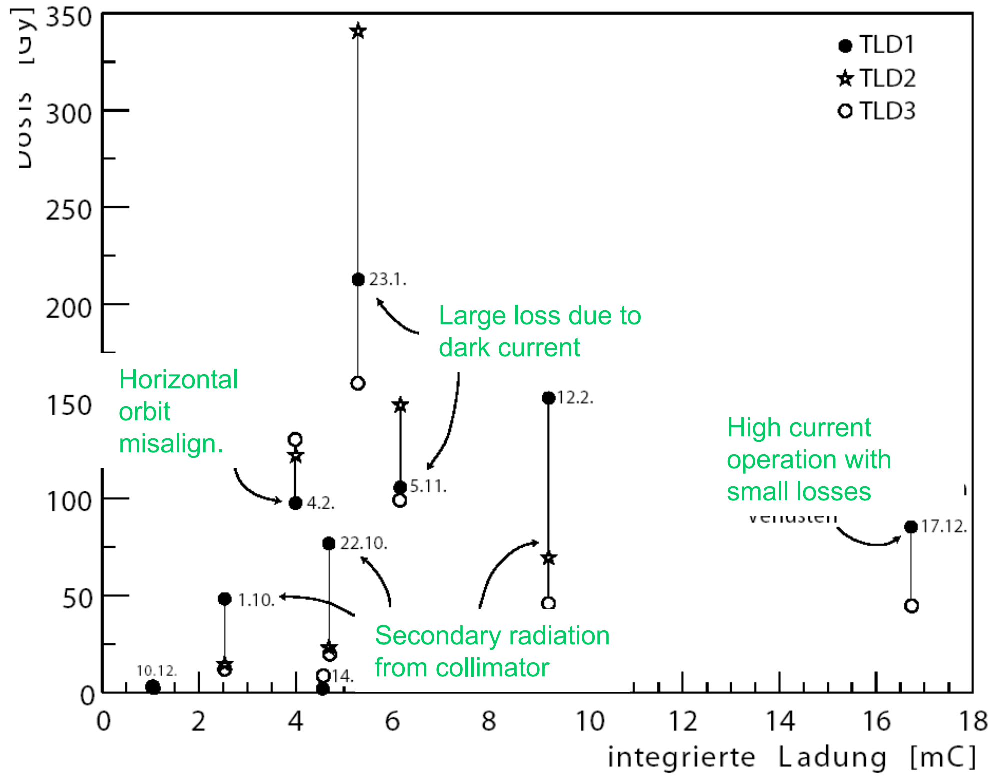
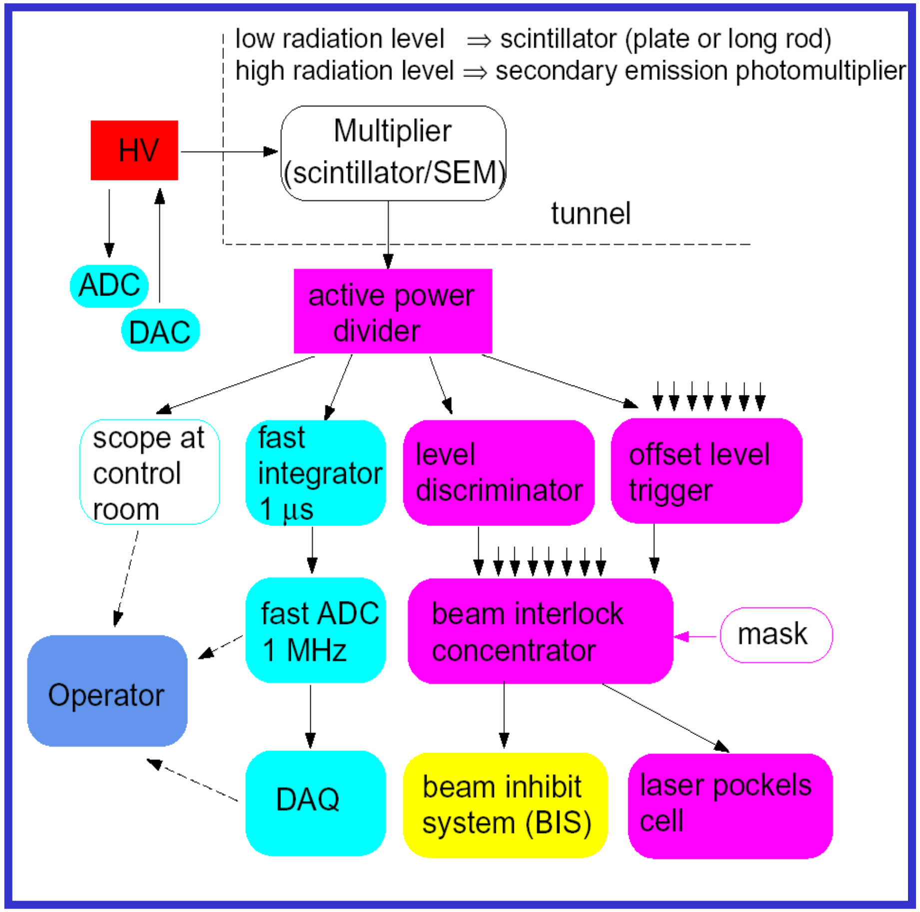


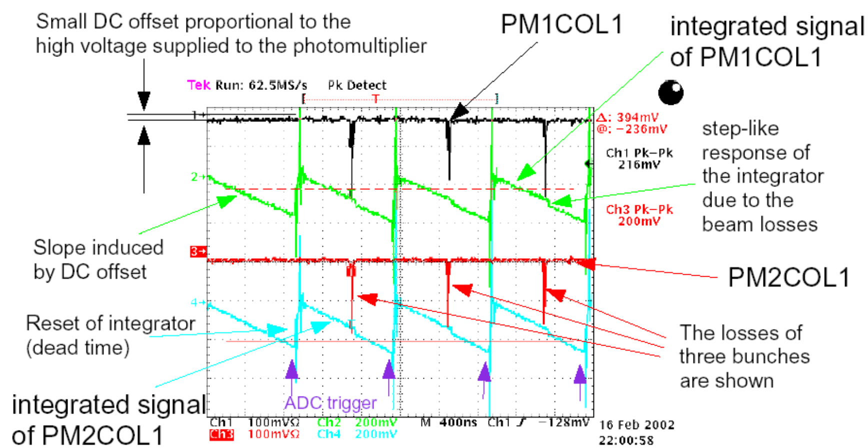
Figure 2: The first three dosimeter values are plotted agains the integrated charge. Different sources of beam losses can be identified by the ration of the dosemeter values.

Beam Loss Monitor System
- Layout -



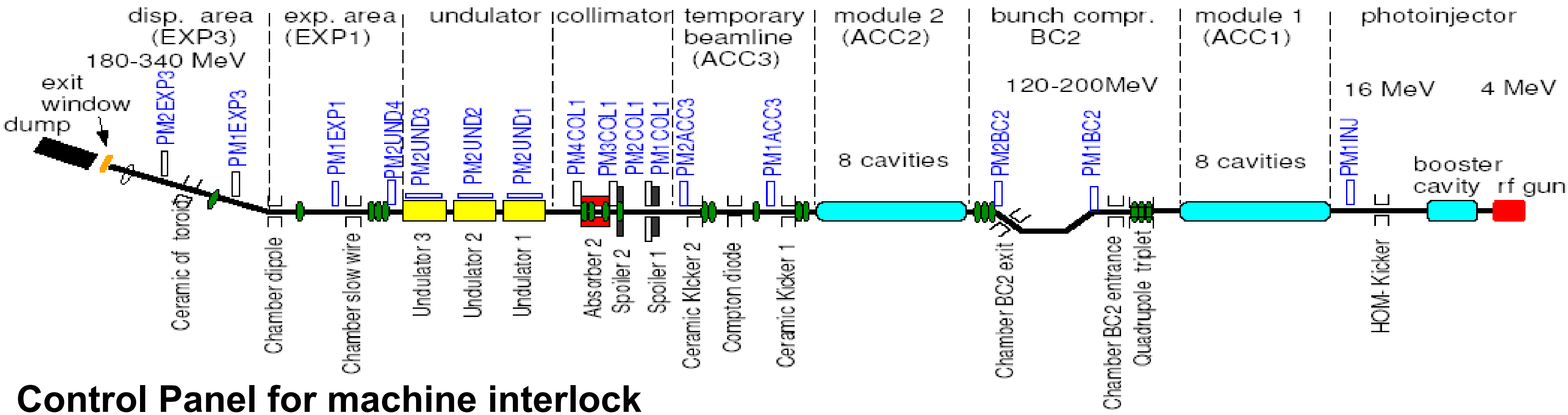
- Secondary emission or photo-multiplier used
- Full integrated to beam inhibit system (BIS)
- 10 µs beam allowed (mask)
- 2.2 µs reaction time

Signal Processing:

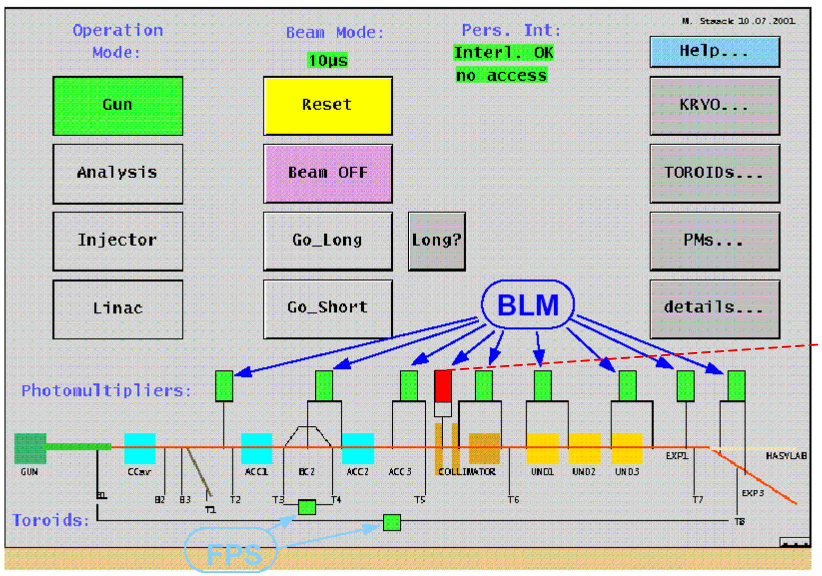


Beam Loss Monitor System

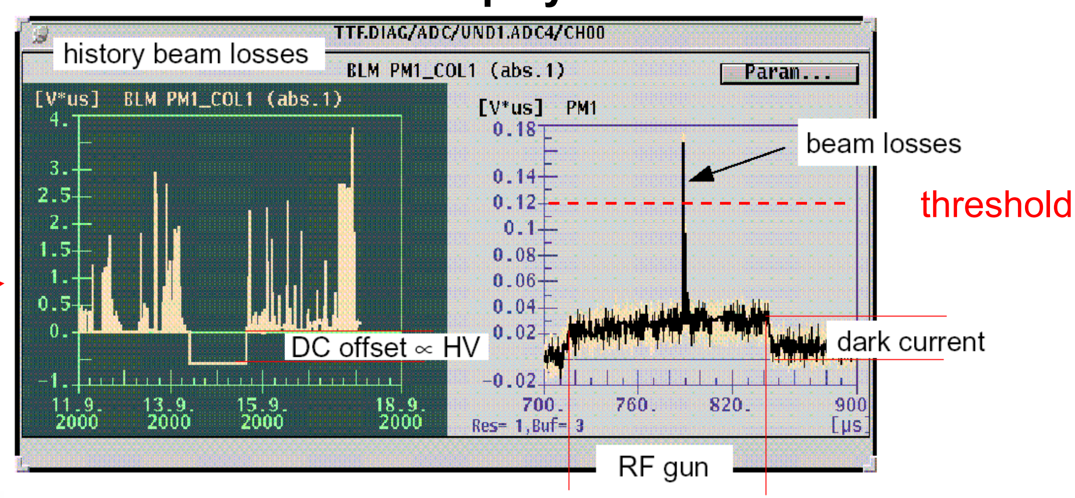
- Loss monitor distribution -



Control Panel for machine interlock



Beam loss monitor display

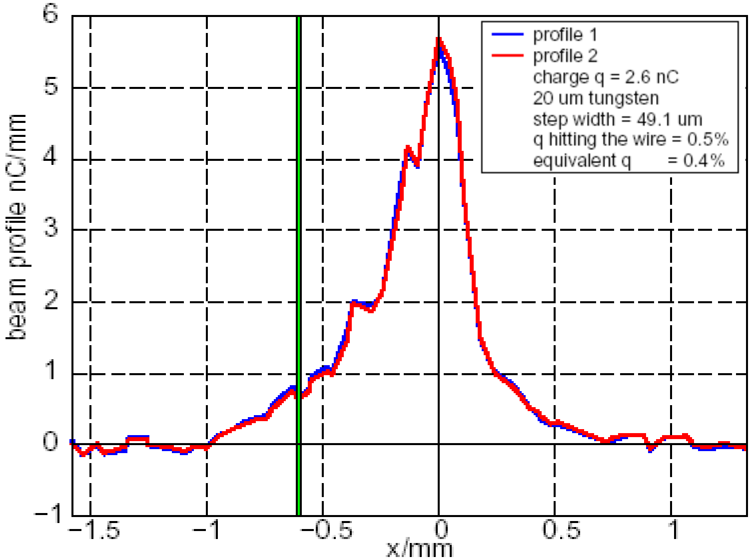


Beam Loss Monitor System
- PM-calibration -

- ***PM with resolutions of 0.5% ⇒ calibration using difference between up and down-stream toroids***

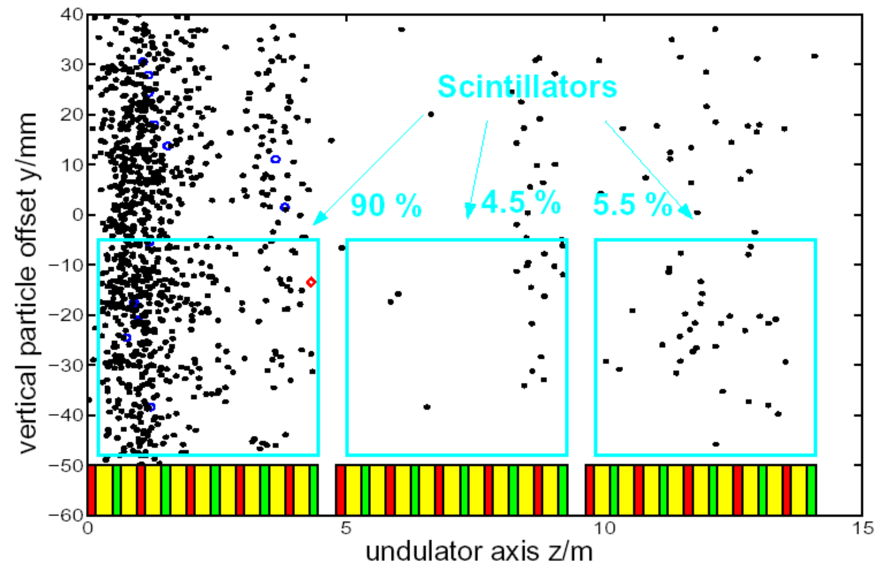
- ***PM with resolutions below 0.5% ⇒ induce small beam losses in controlled way***

Wire scanner profile



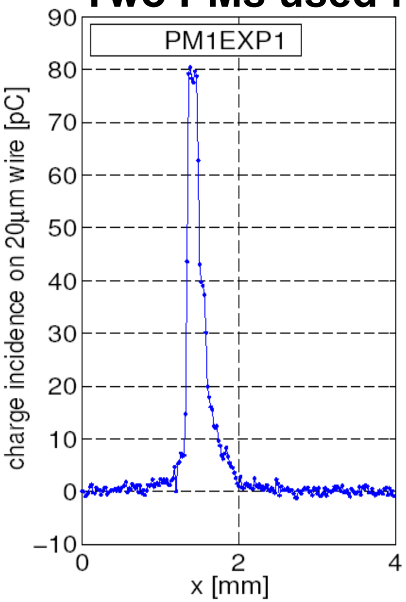
90% of charge hitting the wire is lost in undulator

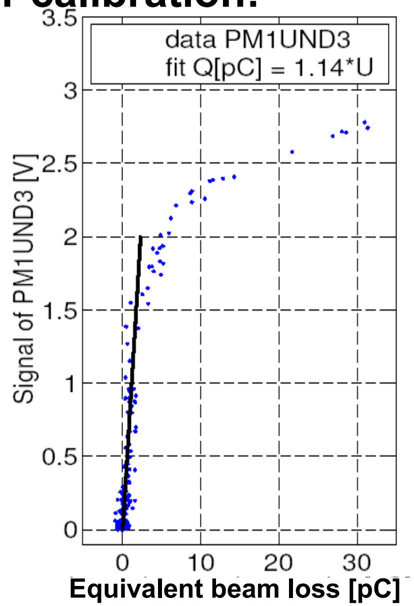
Wire scanner induced losses (simul.)

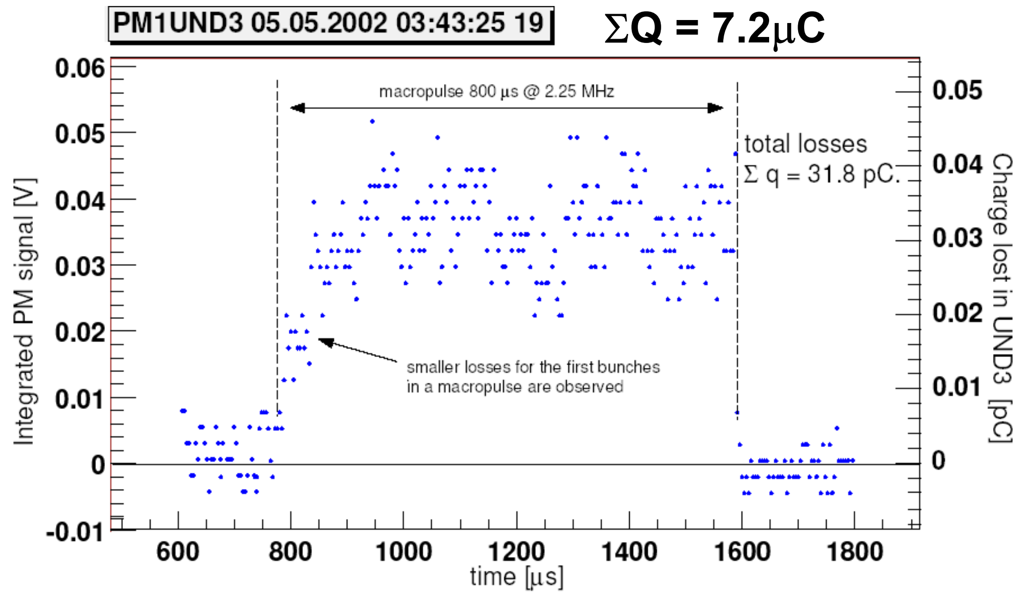


Beam Loss Monitor System
PM-calibration

Two PMs used for calibration:







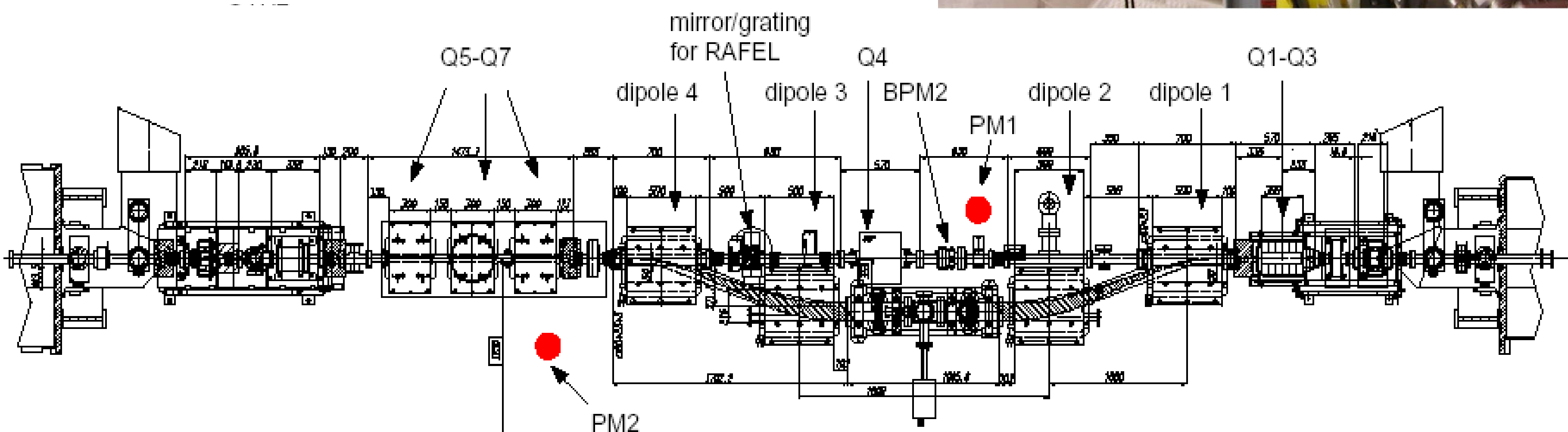
- Interlock levels can be adjusted to resolve 10e-6 losses in the undulator region
- Limited by back ground radiation from other locations in the linac
- Fully integrated to TTF interlock

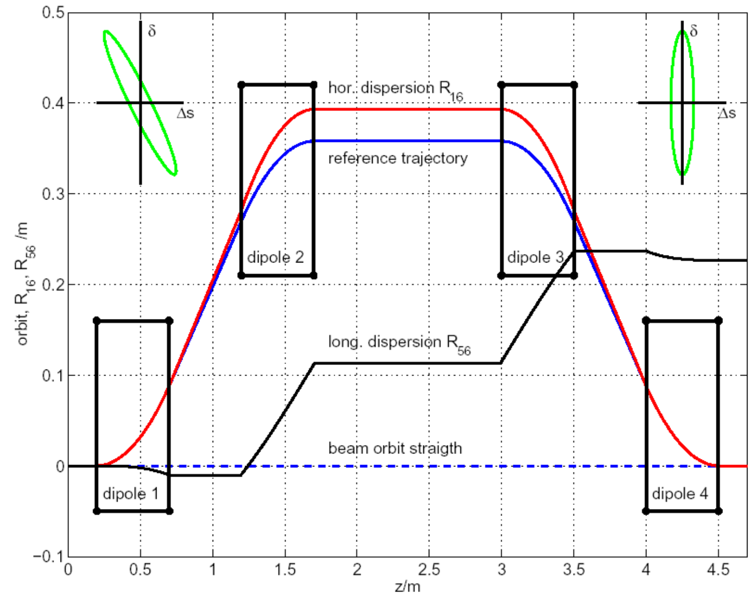
After disassembly of undulator, no field degradation has been measure (integr. depos. dose ~ 30kGy)

Conclusion

Bunch Compressor 2 (BC2)

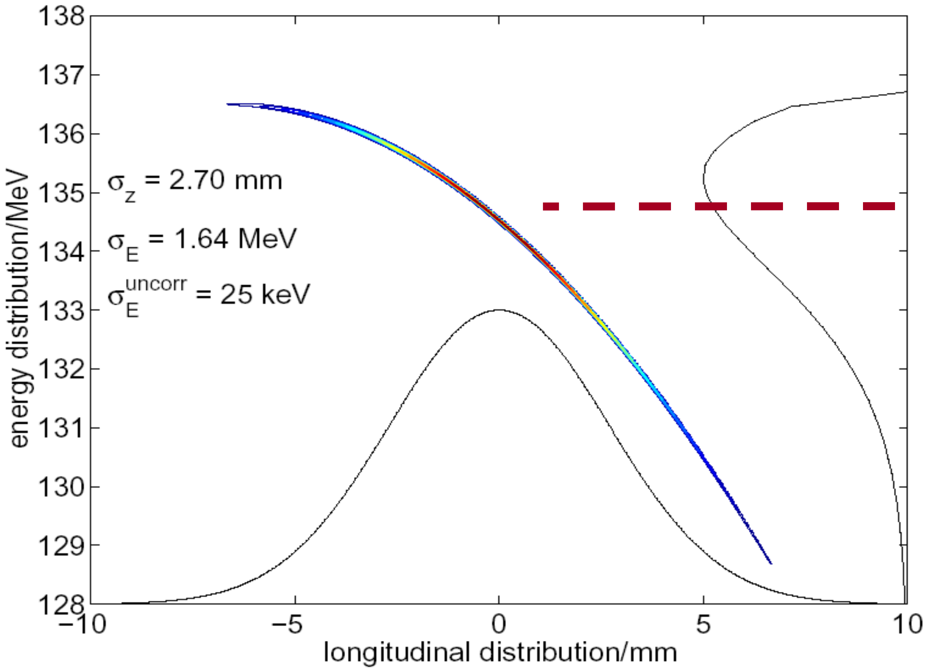
- Nominal bending angle 20 deg.
- Momentum acceptance -14% to +20%
- Horizontal dispersion 393 mm
- Longitudinal dispersion 227 mm
- Additional path length 105 mm
- Chamber material Al
- Chamber height 23 mm
- Effective dipole length 513 mm
- Distance outer dipoles 487 mm
- Distance inner dipoles 1287 mm

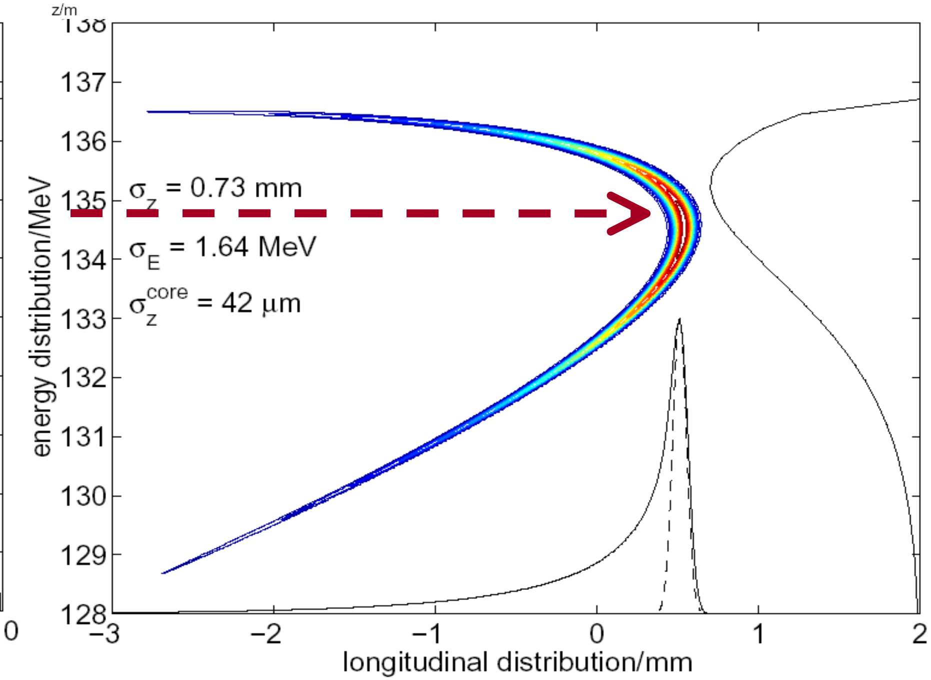




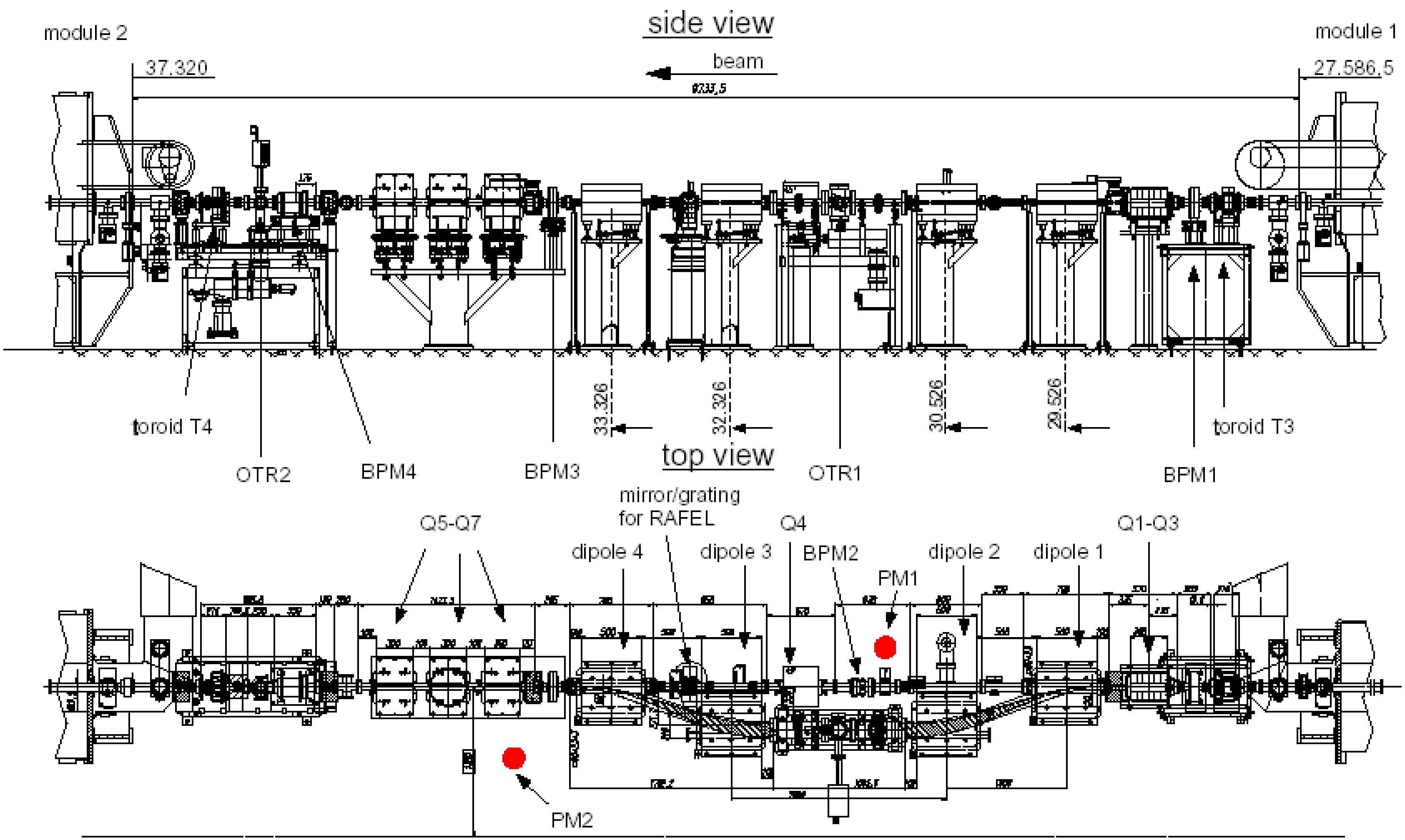
before BC2

after BC2



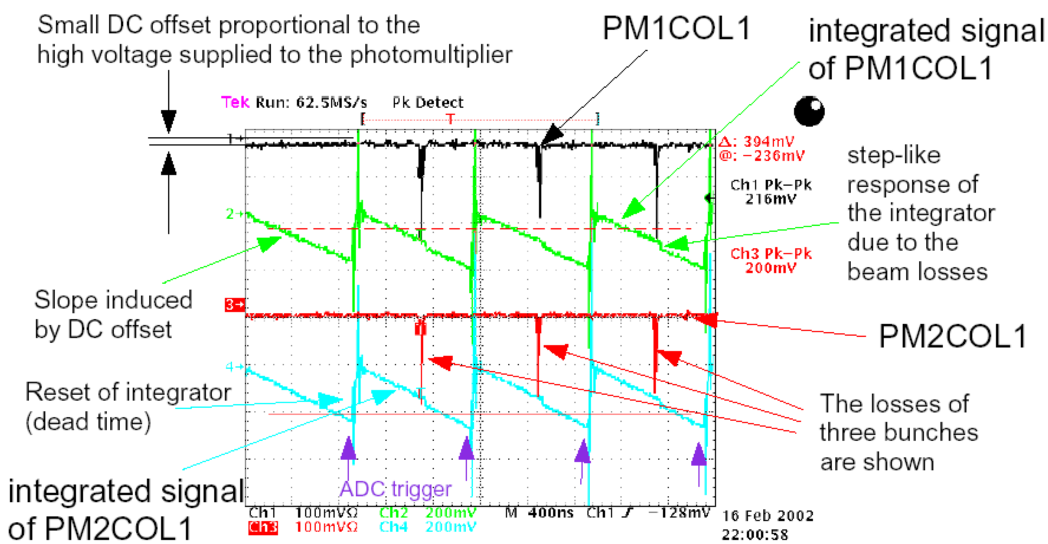


Bunch Compressor 2

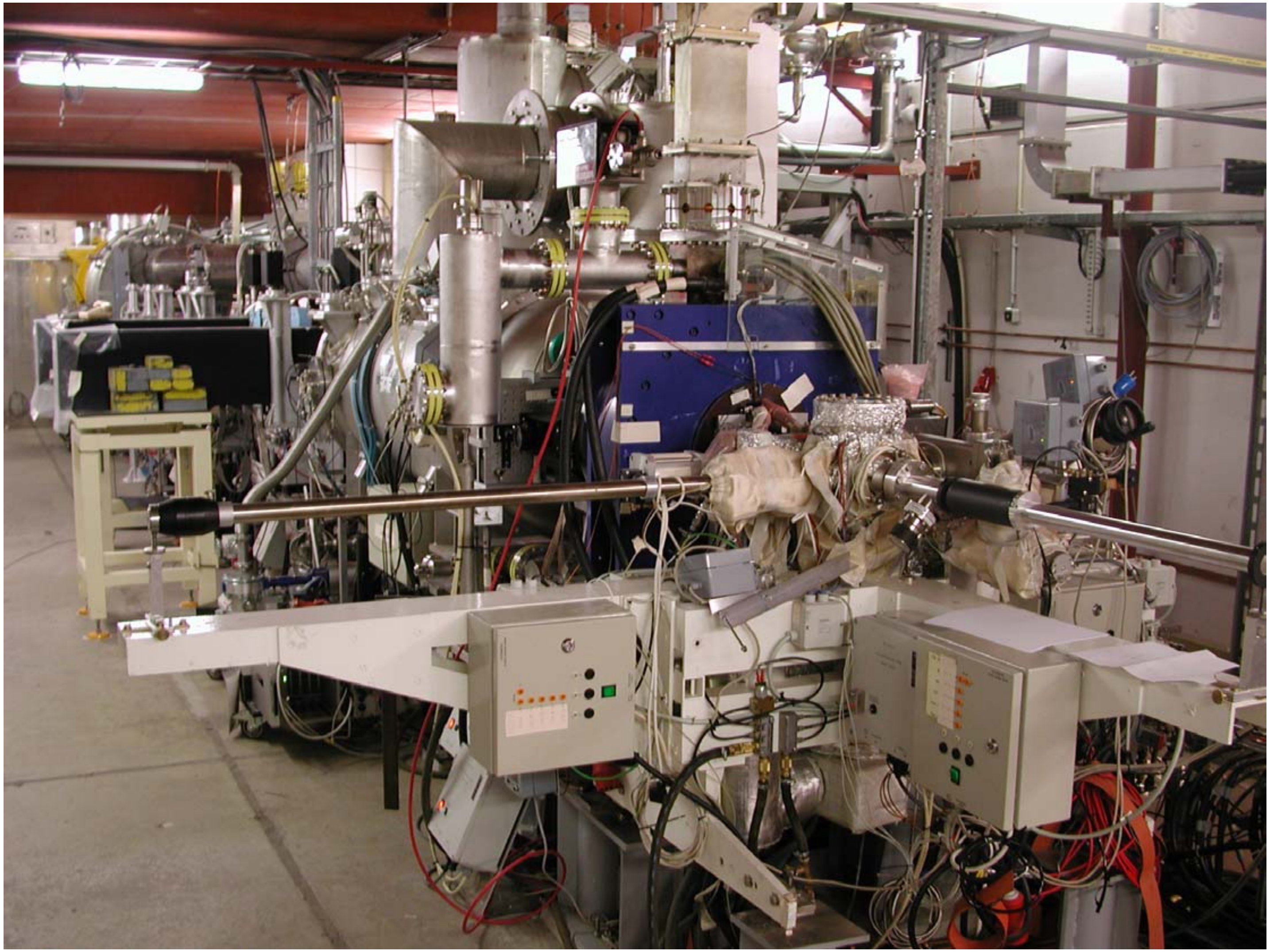


Signal processing

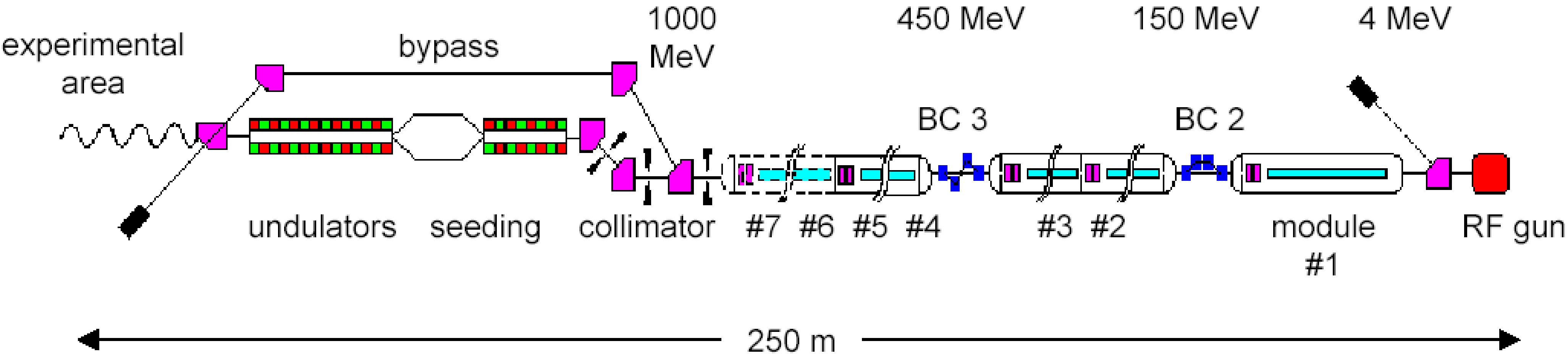
- Signals of PM to fast for ADCs ⇒ gated fast integrator
- Resistive divider adds DC-offset ∝ HV ⇒ controls PM
- Discriminator triggers interlock ⇒ 2.2us to switch off laser



Picture RF-gun and cathode system



TESLA Test Facility Linac Phase II



User facility with photons in the nm range

TTF1

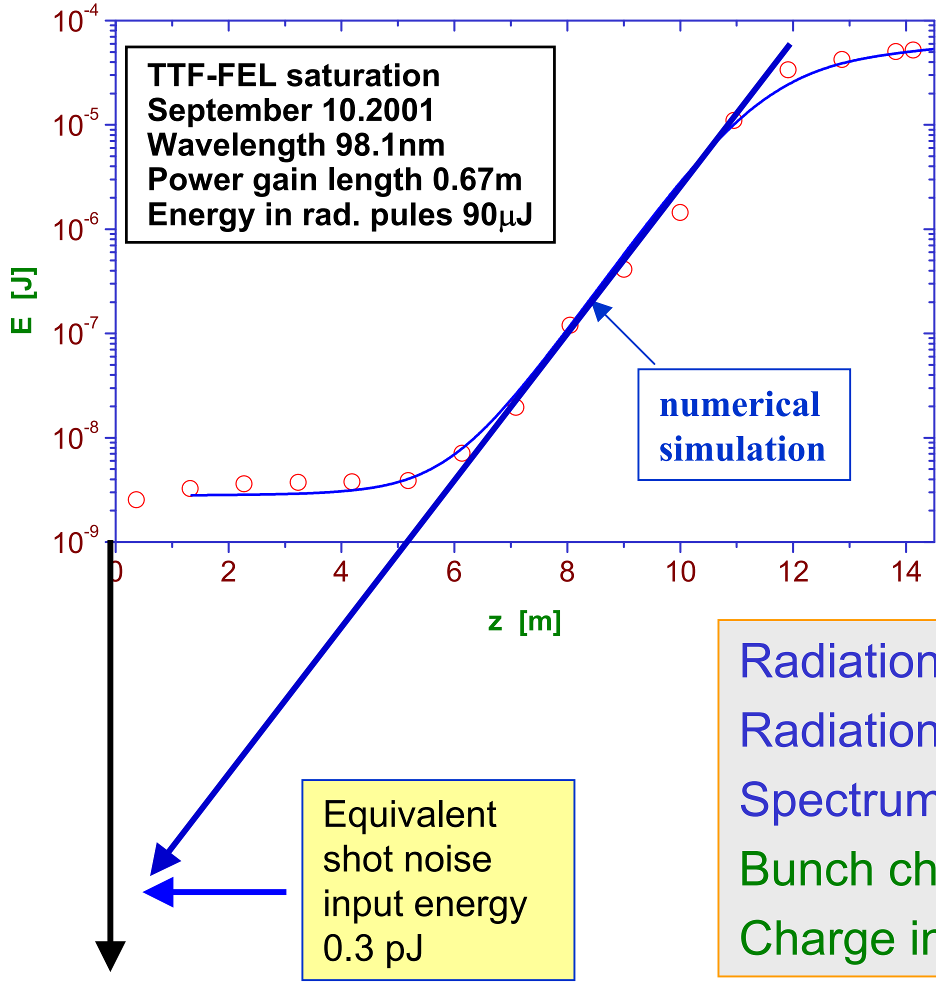
SASE FEL

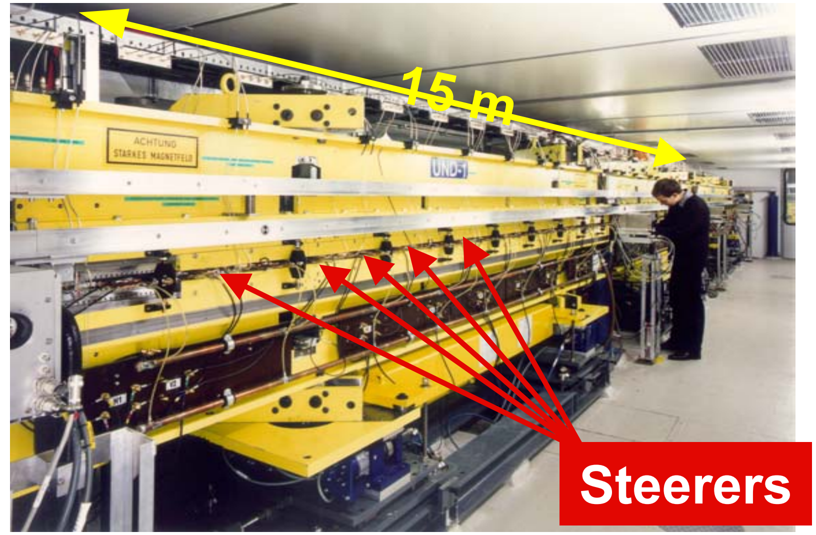
Experimental Hall

Start: 2003/07

Gain Saturation at 80-120 nm

Gain process can be interrupted by 15 steering magnets:





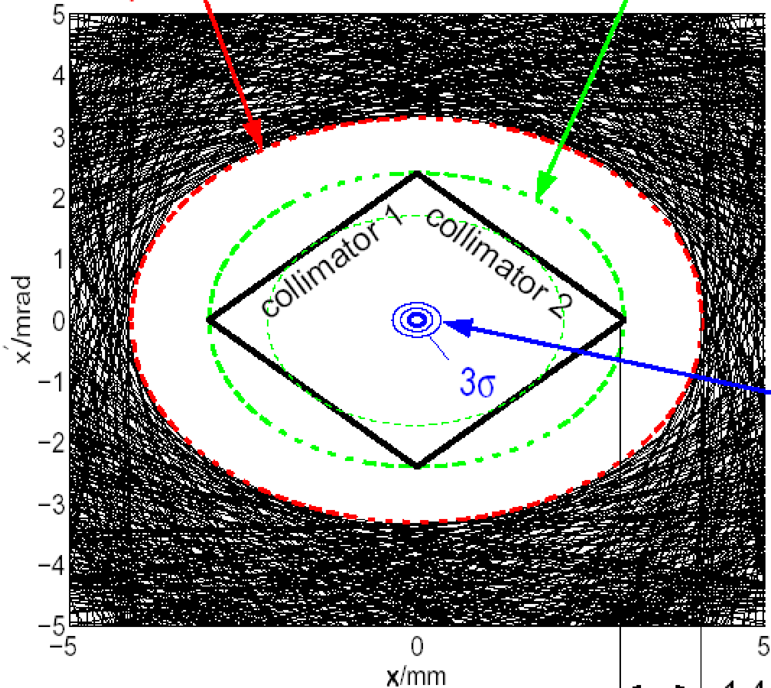
Radiation pulse duration (FWHM)	30-100 fs
Radiation peak power	1 GW
Spectrum width	1 %
Bunch charge	2.8 nC
Charge in radiative part of bunch	0.2 nC

Performance of the collimator

- Phase space acceptance

inner acceptance phase ellipse of undulator a^{und} = 13.8 µm (β^{und} , α^{und})

outer acceptance phase ellipse of collimator $2 \cdot a^{col}$ = 7.7 µm (β^{col} , α^{col})

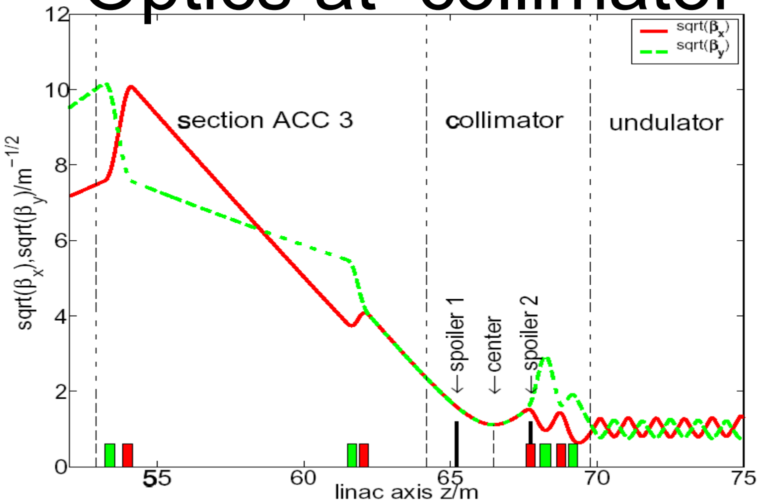


electron beam ε_x = 0.011 µm or norm. ε_x^N = 5 µm (β^{beam} , α^{beam})

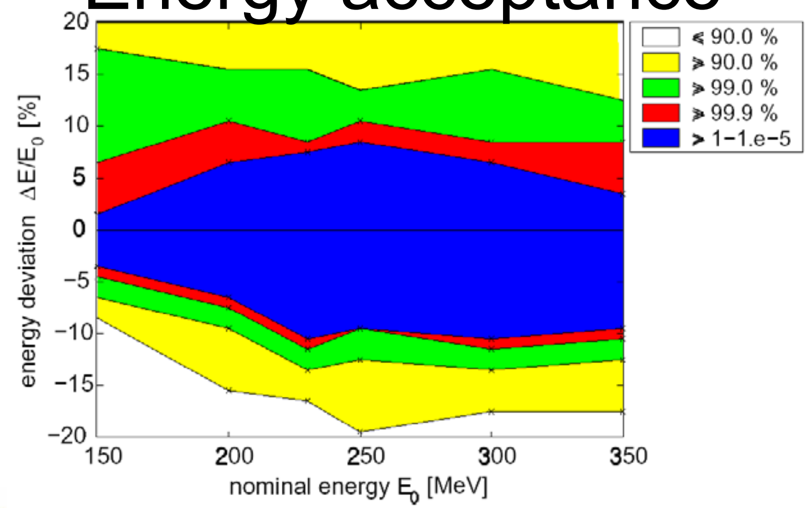
(E = 230 MeV)

1.4 mm clearance inside the undulator

- Optics at collimator

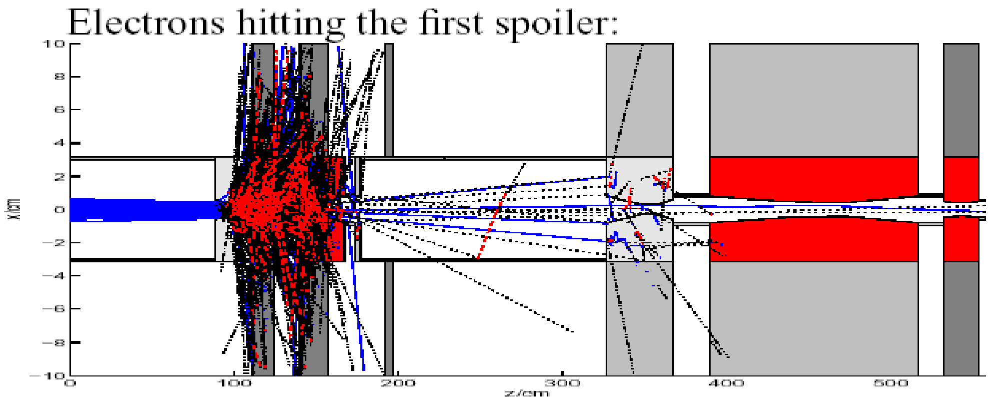


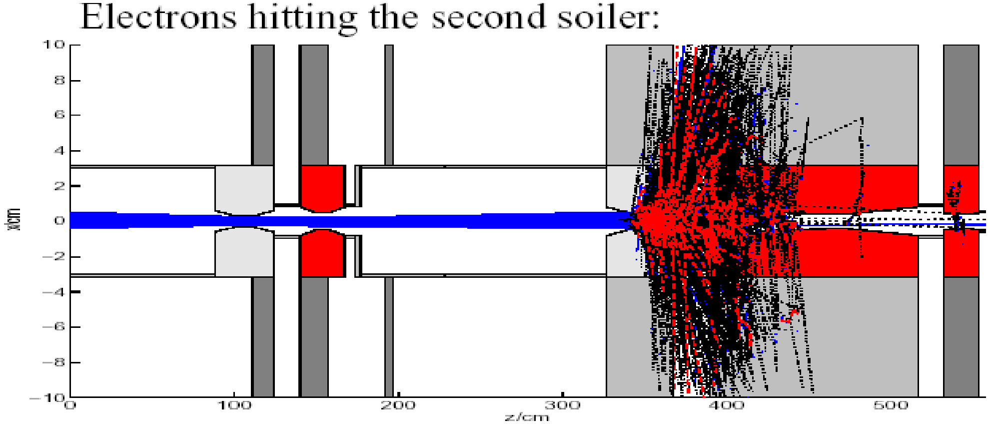
- Energy acceptance

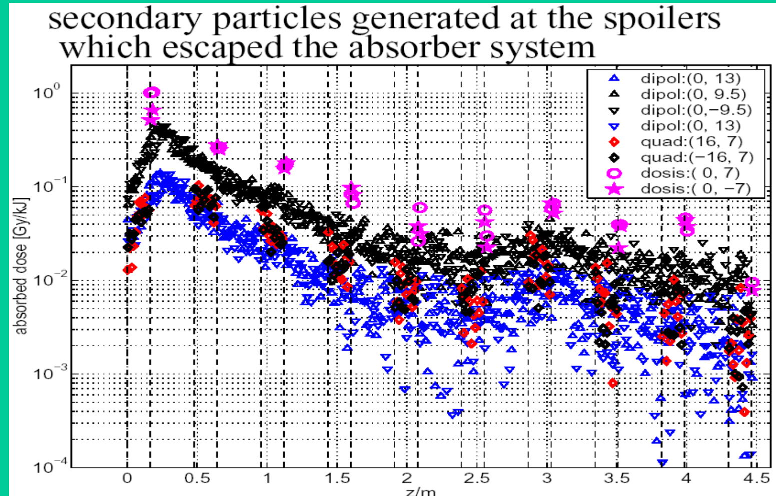


Tracking of secondary particles

- EM-shower in collimator and undulator are simulated

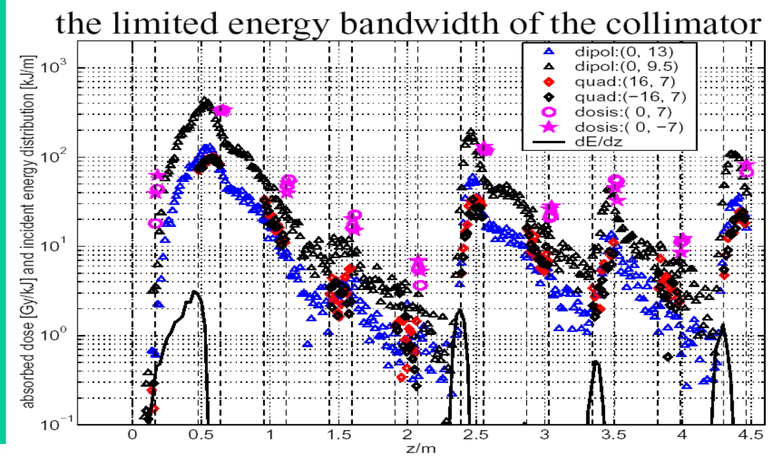






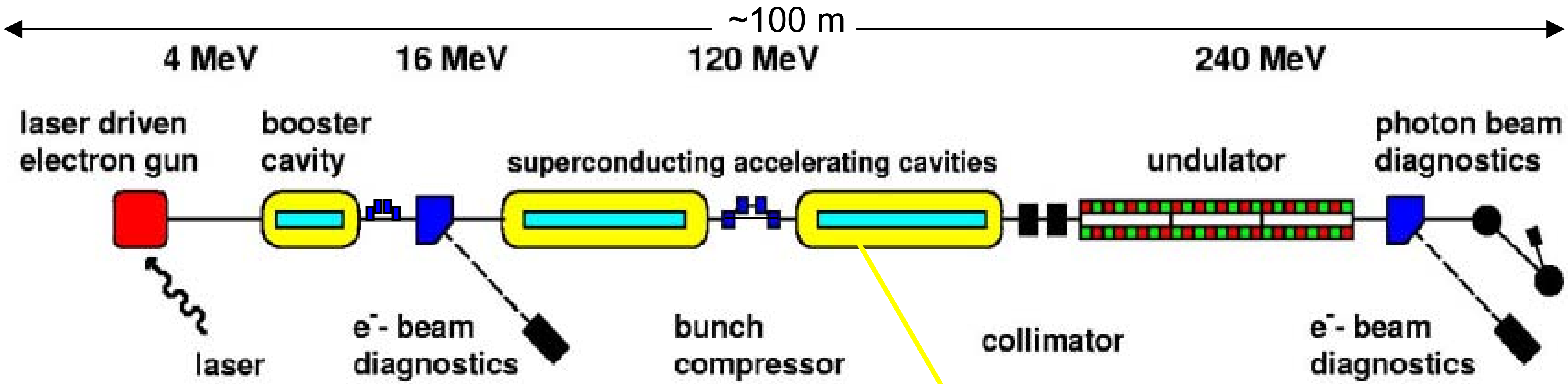
beam

Energy deposition along the undulator



About 0.13% of the incoming beam energy escape the absorber and is dumped in the undulator

Scheme of TTF Linac Phase I



Goals:

a) Test Facility for SC-modules

b) Proof-of-principle of SASE-FEL

TTF Linac:

- RF photo injector
- Two SC-acceleration modules
- Bunch compressor (BC2)
- Collimation system
- Three undulator modules

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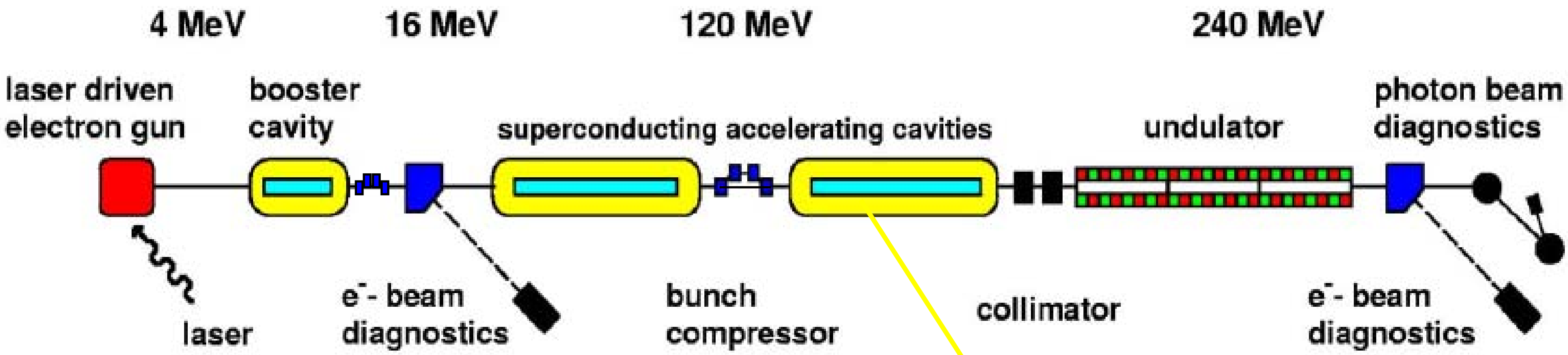


Goals:

a) **Test Facility for SC modules**

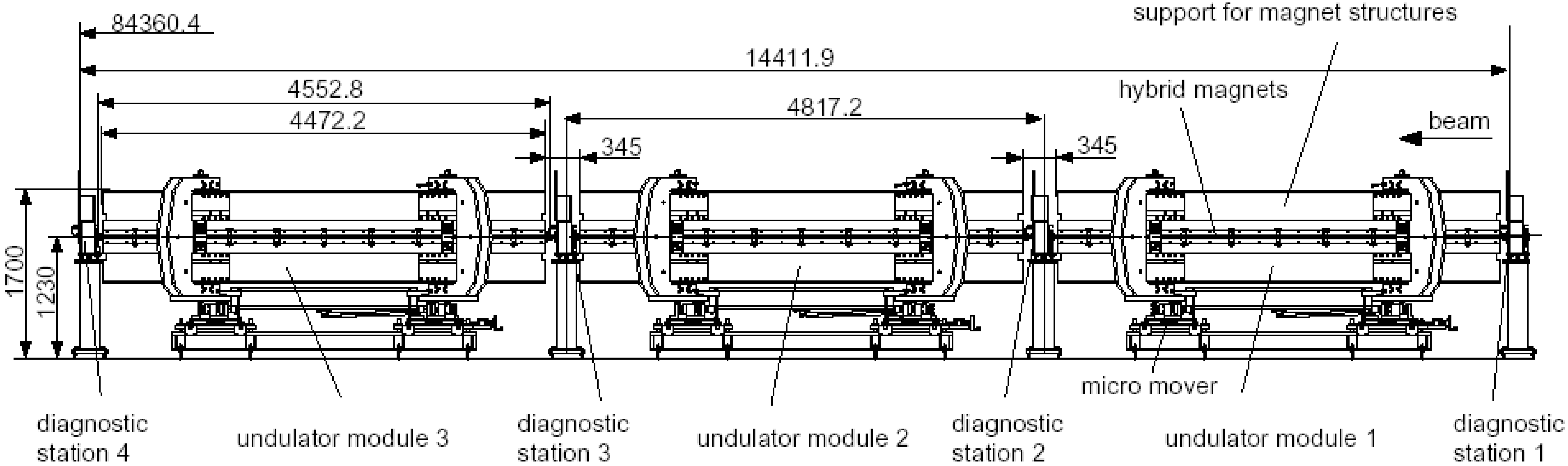
b) **Proof-of-principle of SASE-FEL**

Linac:

- **RF photo injector**
- **Two SC-acceleration modules**
- **Bunch compressor (BC2)**
- **Collimation system**
- **Three undulator modules**

I=8mA, Δt=800μs,

Undulator Modules



number of segments		3
period length	λ_u	27.3 mm
number of poles		327
undulator peak field	B_0	0.4582 T
undulator rms field	B_{rms}	0.3210 T
average K-value of undulator	K_{rms}	0.8184
average quadrupole gradient	g_{mean}	10.497 T/m
length of quadrupole	l_q	163.8 mm
length of FODO-cell	λ_{FODO}	955.5 mm
undulator gap height	h	12 mm
vacuum chamber radius	R_{und}	4.75 mm